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Development of Laboratory Equipment and protocols for the Assessment of Rain, Water Wash-Down, and Channelized Flow for Removal of Spores on Urban Surfaces

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Development of Laboratory Equipment and Protocols for the Assessment of Rain, Water Wash-Down, and Channelized Flow for Removal of Spores on Urban Surfaces

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Acronyms and Abbreviations

ADA	aerosol dose apparatus
Ba	*Bacillus anthracis*
Bg	*Bacillus globigii*
Btk	*Bacillus thuringiensis* var. *kurstaki*
CONUS	Continental United States
EPA	U.S. Environmental Protection Agency
ft.	foot/feet
h	hour(s)
HSRP	Homeland Security Research Program
ID	identification
in.	inch(es)
ISO	International Organization for Standardization
L	liter(s)
m	meter(s)
µm	micrometer(s)
MDI	metered dose inhaler
mL	milliliter(s)
mm	millimeter(s)
MOP	miscellaneous operating procedure
NHSRC	National Homeland Security Research Center
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
ORD	EPA Office of Research and Development
Parsivel	PARticle SIze and VELocity
PBST	Phosphate buffered saline with 0.05% Tween® 20
PDAQ	portable data acquisition
PVC	polyvinyl chloride
QAPP	Quality Assurance Project Plan
RTP	Research Triangle Park
s	second(s)
SCS	U.S. Soil Conservation Service
TSA	tryptic soy agar
WACOR	Work Assignment Contracting Officer's Representative

Executive Summary

A large-scale outdoor biological contamination incident requires a better understanding of how rainfall and water-based decontamination measures would transport contaminants so that responders can effectively select sampling locations, stage waste, and strategize other recovery decisions. Over the last few years, the United States Environmental Protection Agency's (EPA's) Homeland Security Research Program (HSRP), in the Office of Research and Development (ORD), has built and characterized a laboratory-scale rainfall simulator and a channelized flow simulator. HSRP has also developed bench-scale power washing testing protocols to study the movement of *Bacillus anthracis (Ba)* simulants. The primary focus of this report is to document the characterization of these apparatuses and discuss the future direction of this work.

Few commercial rainfall simulators are on the market, therefore a custom 10-ft. tall rainfall simulator was constructed and tested with ten different nozzle configurations over a range of operating pressures. Various-sized collection bins and a PARticle SIze and VELocity (Parsivel) laser disdrometer (version 2) were used to characterize the simulator for rainfall intensity, particle size, and velocity. The simulator produced rain events with an intensity range of 0.9 – 6.5 inches (in.)/hour(h). Preliminary washoff experiments were conducted by inoculating concrete coupons (using a meter dosed inhaler and aerosol deposition device) with *Bacillus globigii (Bg)*, a simulant for *Ba* often used in disinfection studies. These spore washoff experiments removed approximately 5-45% of spores from the coupons within the hour-long testing window. However, there was no predictable pattern of spore removal by rainfall intensity.

A 26-ft. tall rainfall simulator was therefore constructed to improve the critical shortcomings (i.e., droplets failing to reach terminal velocity) of the 10-ft. simulator. The 26-ft. tall simulator was capable of producing rain events that were 0.66 - 4 in./h in intensity. This rainfall range is in line with being able to simulate up to 100-year, one-hour storm events experienced across the majority of the continental United States. Currently, 32 coupons (concrete and asphalt) have been inoculated with *Bg* or *Bacillus thurengiensis kurstaki (Btk)*, subjected to simulated rain events, and had spore concentrations quantified in the resulting runoff water. The results of these tests were provided in the Appendices of this report and will be elaborated upon in forthcoming publications. Future planned experiments will include rain patterns that involve periods of drying and variations in rain intensity values.

A custom channelized flow simulator was constructed, and spore washoff experiments were performed using concrete coupons inoculated with *Bg* for flows ranging from 25 – 150 milliliters) (mL)/second (s). Over the course of an hour, approximately 18-35% of spores were removed from the coupons. However, there were large variations in removal that did not strictly follow a pattern according to flowrate. A specialized, hydraulically more flexible, benchtop sediment transport channel was acquired to continue this work using velocities at, above, and below the predicted threshold of movement.

Highly controlled bench scale spray washing procedures were also evaluated using a load cell to measure the force of the spray applied. A conventional power washer and garden hose were used, and brick, asphalt, glass, and concrete coupons inoculated with *Bg* were tested. At most, 15% of the spores were removed from the coupon during testing as measured in the runoff water. For concrete, the total removal was like lower intensity rain events but in a much shorter amount of time. Experiments examining *Btk* removal are currently underway. Future work will involve outdoor testing and explore the use of surfactants as a wash aid.

1.0 Introduction

The best manner for emergency responders to efficiently and effectively decontaminate a large outdoor area after a biological release of *Bacillus anthracis (Ba)* spores is uncertain, both in terms of technology and process. A large-scale remediation effort will likely take a considerable length of time to plan and execute. During this time, there is an opportunity for rainfall events to redistribute contamination. Limited national laboratory capacity and high costs will require decision makers to target sample locations so maps that highlight potential hotspots this over time and weather event are desirable. Additional examples of decisions that would be aided by fate and transport predictions are waste staging locations (i.e., it would be undesirable if waste areas flooded and washed contamination into clean areas) and evacuation zone delineation. Contaminate spread due to water may also occur because decision makers choose to pursue interventions that use water-based washing methods to decontaminate critical outdoor spaces. Since 2016, the United States Environmental Protection Agency's (EPA's) National Homeland Security Research Center (NHSRC) has built laboratory capabilities to better understand and compare the removal of spores from urban surfaces by rain, channelized flow, and washing (using spray generated from a garden hose and a pressure washer). During this process, several iterations of custom laboratory equipment and processes were developed. The custom equipment described in this report was designed and built for these experiments, due to few available off-the-shelf options. The purpose of this report is to document the characterization of this custom-built equipment and related processes. As such, this report is separated into three main sections: 1) Rainfall, 2) Overland Flow, and 3) Spray-Down. While biological washoff data have been collected as part of each stage of this work, this topic is not the focus of this report. Washoff data are provided in the main body of text only when necessary to illustrate a point relevant to equipment redesign. However, all washoff data recorded to-date are provided in full detail in the appendices. These data are still actively being collected. Once complete, several additional publications thoroughly analyzing these data and providing conclusions and recommendations regarding the efficacy of different water-based methods at removing spores are planned in upcoming years. Experiments are also planned to study the removal of spores by different patterns of rain and dry periods and more complex water matrices.

2.0 Background

2.1 Rainfall

While the current scientific literature lacks research specifically studying the removal of spores by various water sources (i.e., rain droplets, channelized flow, or spray), there is a wealth of studies examining the erosivity of soil by rainfall and the washoff of solids from impervious surfaces by stormwater (e.g., Egodawatta et al., 2007; Shaw et al., 2009; Charbeneau and Barrett, 2016; Gong et al., 2016). Soil erosivity and stormwater washoff have been shown to depend on rainfall intensity, drop size distribution, and kinetic energy (van Dijk et al., 2002, Panagos et al., 2017, Wischmeier et al., 1958). Other parameters such as pH, temperature, and organic and inorganic composition of stormwater may also influence washoff but have not been studied in detail. Rainfall parameters vary by climatic region across the United States. In any two-year period, most locations in the continental United States (CONUS) experience less than two in. of rainfall within any one-hour storm event (Figure 2.1). The largest rain event that most places in the CONUS will experience within a one-hundred-year period is approximately 4 in./h, excluding coastal regions in the southeast and south-central U.S./great plains, likely due to thunderstorm activity or mesoscale convective systems that last for longer than one hour (Figure 2.2). Very high intensity rainfall values are, however, possible over very short periods of time.

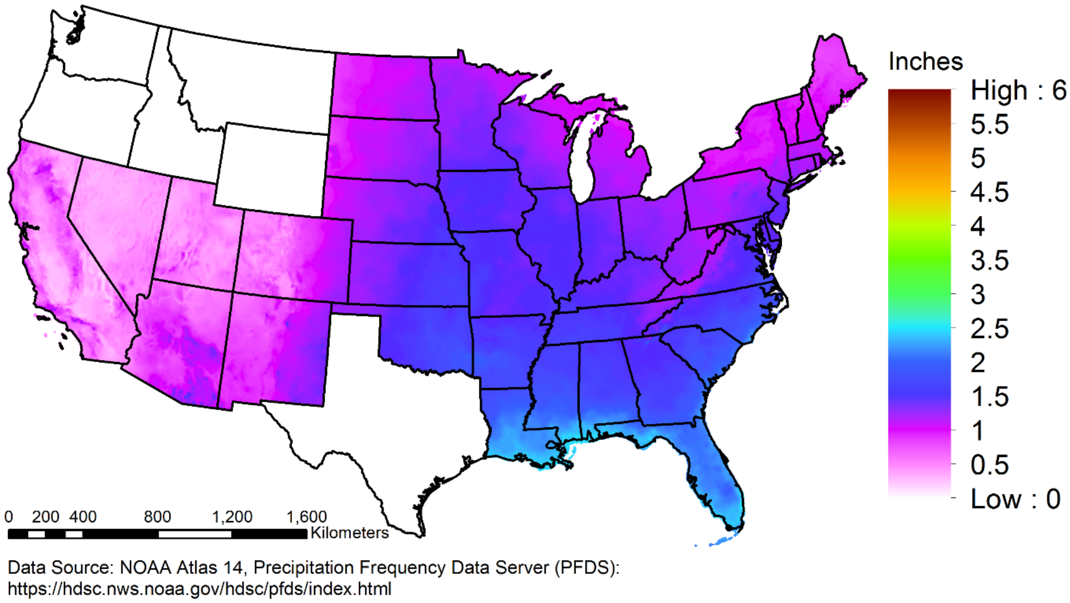

Figure 2.1 Continental US precipitation frequency estimate for a two-year recurrence interval and a one-hour duration rain event. (States in white are not yet covered by National Oceanic and Atmospheric Administration's (NOAA's) Atlas 14 program, but there are active plans to include them in the future.)

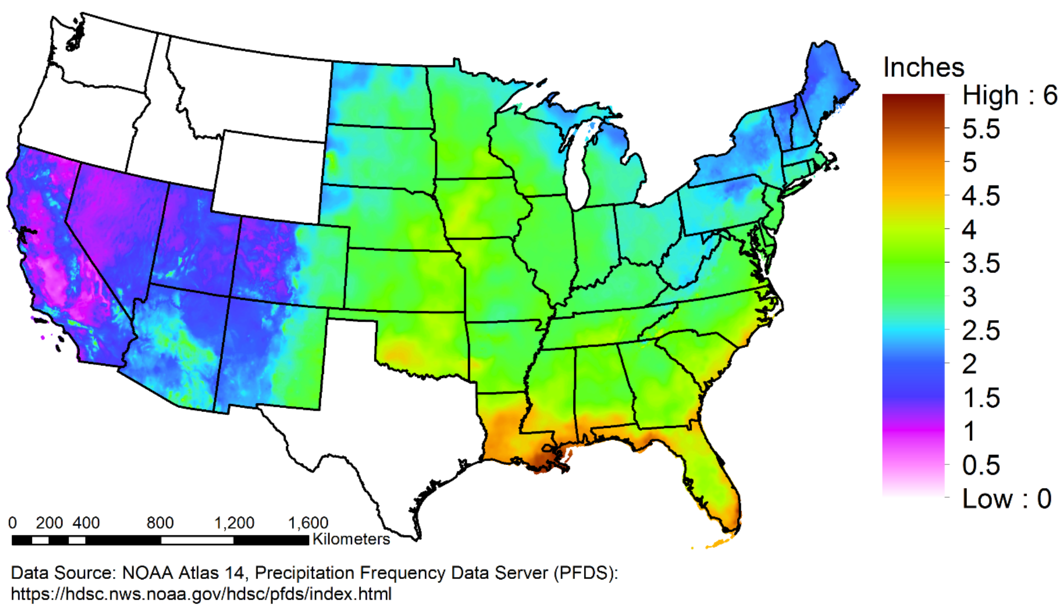

Figure 2.2 Continental US precipitation frequency estimate for a 100-year recurrence interval and a one-hour duration rain event. (States in white are not yet covered by NOAA's Atlas 14 program, but there are active plans to include them in the future.)

It is important to recognize that intensity is inherently a bulk parameter for rainfall. To characterize rainfall in more detail (and understand particle detachment and washoff), droplet size and velocity measurements are necessary. These fundamental parameters also vary by geography and meteorological event, but the energy relationships and size frequency distributions that dictate natural rainfall have been studied in detail since the 1940s (Laws, 1941; Laws and Parsons, 1943). In general, raindrops have median drop size values of less than 4 millimeters (mm) and have corresponding terminal velocities of less than 9 meters (m)/s (van Dijk *et al.*, 2002). Both values were considered key design criteria for this work.

Over time, rainfall simulators have been constructed in a variety of different styles. Bowyer-Bower and Burt (1989) and Hall (1970) provide comprehensive reviews of rainfall simulator designs. In brief, early standard devices were introduced by the United States Soil Conservation Service (SCS) during the 1930s and 1940s and called the "type F" and "type FA." These standard devices consisted of two parallel lines of nozzles on each side of an agricultural study plot that were directed upward to reach a 10-foot maximum spray height before falling to the ground surface. Type FA worked at reduced pressure compared to the type F, so Type FA was ultimately favored because it was less expensive to operate. While these devices achieved intensity values that mimicked naturally-occurring rain events, the drop sizes generated from the nozzles corresponded only to droplets experienced during lower intensity rain events. Also, their velocities were lower than the terminal velocities achieved in the natural environment, indicating that the overall kinetic energy delivered during simulated rain events was not representative of natural rainstorms and potentially underestimated erosivity resulting from the storm events. To overcome these shortfalls, artificial rain simulators have evolved creatively. One device used muslin fabric draped over a horizontal screen of chicken wire with lengths of yarn attached to the fabric to form larger droplet sizes (Ellison and Pomerene, 1944). Others have used spray nozzles on a rotating disk (Pall et al., 1983) and telescopic stainless-steel tubing with redistribution screens (Regmi and Thompson, 2000).

2.2 Channelized Flow

Overland flow of water, also commonly referred to as sheet flow or surface runoff, results when water cannot infiltrate into the ground and instead moves along the land surface. Hydraulically, surface runoff is defined as unsteady, shallow, open-channel flow and is represented mathematically by the Saint-Venant equations (Néelz and Pender, 2009). The flow of surface runoff is also considered turbulent. The fundamental mechanisms of solids removal during urban area channelized overland flow (e.g., in roadway gutters) is not a mature area of study. However, it is reasonable to consider that this area of solids removal shares some of the mechanistic underpinnings established in the study of sediment transport in river channels, a more robust field of study. In river sediment transport, the Shields diagram (and variations thereof, including the Hjulström-Sundbog diagram) (Cao et al., 2006) graphically displays the threshold for the start of sediment movement. Depending on the version of the diagram, the y-axis is provided as either a dimensionless constant such as a Reynolds number, shear stress, or velocity. The x-axis represents the diameter of the particle and shading of the diagram indicates how properties of the flow or sediment affect the threshold of particle movement. If *Bacillus anthracis* (*Ba*) spores (approximate spherical equivalent diameter of 1 micrometer (μm) [Chung et al., 2009]) are assumed to behave like unconsolidated sediment, their movement would start at approximately 0.18 m/s in water (Southard, 2006).

3.0 Rainfall

3.1 Characterization Techniques

In the past, researchers have characterized rain drops using a combination of complementary techniques including water-staining paper, pelletizing flour, photographic methods, and disdrometers (Kathiravelu et al., 2016). During this project, key rainfall simulator parameters and design goals (Table 3.1) were evaluated using three measurement techniques: one collection bin, a Parsivel^2 disdrometer (OTT Hydromet, Loveland, CO, USA) and many small rain collection bins (used to produce an intensity heat map). (Note, the superscript "2" on the Parsivel indicates that it was the second generation of laser in the Parsivel disdrometer. This notation is the convention used by OTT Hydromet to distinguish between their two products) The Gunn-Kinzer curve mentioned in Table 3.1 refers to the relationship between droplet size and velocity experienced during natural rainfall events (Gunn and Kinzer, 1949). It is provided for reference in the Parsivel^2's spectra graphing software that (Figure 3.1). Figure 3.2 shows examples of simulated rainfall data that did not adhere to the Gunn-Kinzer curve.

Table 3.1 Rainfall Simulator Design Criteria

Parameter	Design Goal	Measurement Technique
Intensity	0.5 – 4 in./h	bin, Parsivel^2 disdrometer
Droplet Size Distribution	follows Gunn- Kinzer curve	Parsivel^2 disdrometer
Droplet Velocity	follows Gunn-Kinzer curve	Parsivel^2 disdrometer
Spray Pattern	spatially uniform intensity	heat map

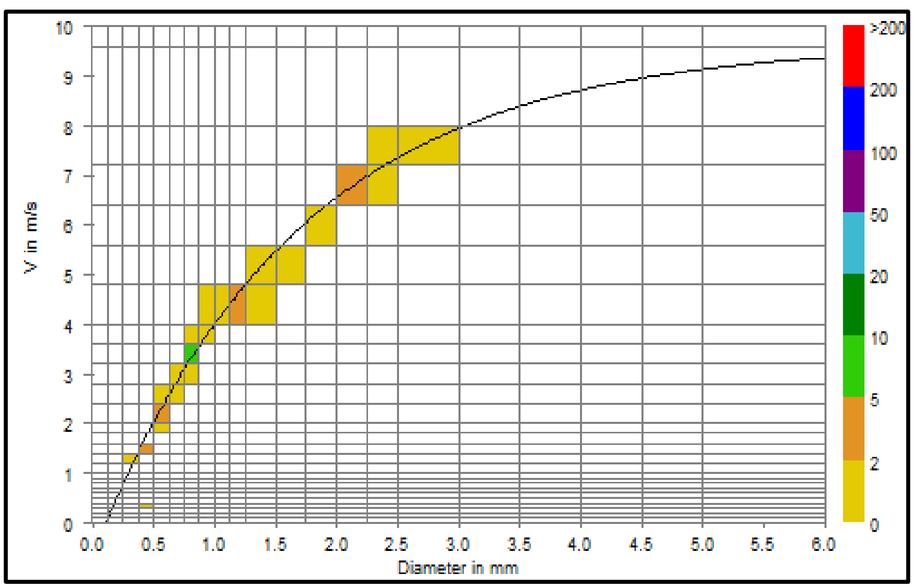

Figure 3.1 10-second Durham, North Carolina, USA rain event data recorded by the Parsivel^2. The black line is the Gunn- Kinzer velocity-diameter reference curve for natural rain events. The colored right-side vertical axis represents the number of rain droplets.

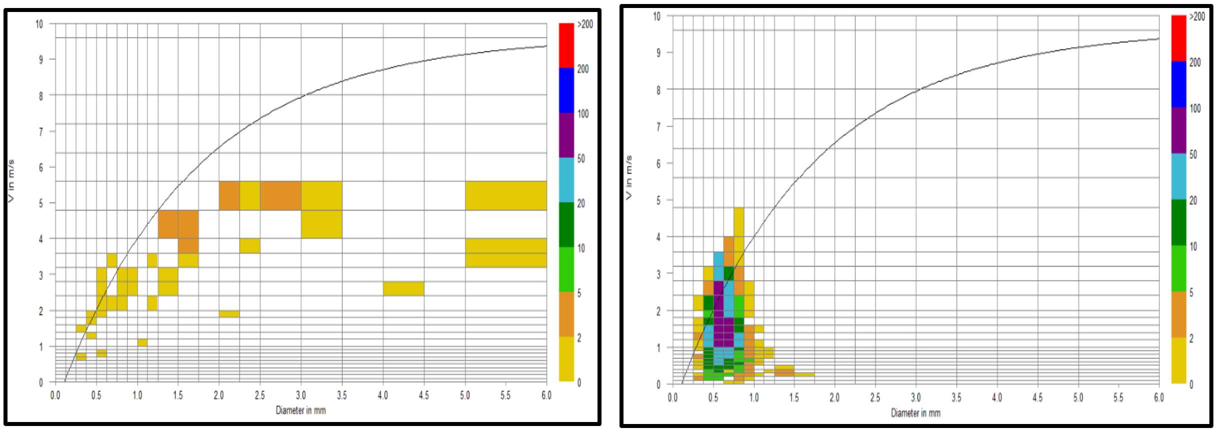

Figure 3.2 Examples of simulated rainfall that did not follow the Gunn-Kinzer curve.

The collection bin consisted of a plastic receptacle of size like the coupons used during washoff experiments (12 in. by 12 in.). Rainfall simulator water (deionized water) was collected in the bin for a recorded duration and used to calculate the rain intensity produced by each nozzle-operating pressure configuration. The Parsivel^2 optical disdrometer was used to measure drop size distribution and velocity. The Parsivel^2 is a laser-based optical system that consists of two sensor heads with splash protectors and measures approximately two feet from the sensor base to the top of the sensor heads (Figure 3.3). One side of the sensor is a laser emitter and the other side is the receiver. The Parsivel^2 laser-based optical system produces a horizontal strip of light approximately 1 in. wide and 7 in. long. If no water droplets are detected between the emitter and receiver, then a maximum voltage output is detected. As precipitation particles pass through the laser beam, a portion of the beam is blocked, which reduces the voltage. This voltage drop is correlated with particle size. The duration of the signal disturbance is also measured and is used to calculate the particle velocity. Velocity and particle size are then used to calculate kinetic energy for each rain event. Recently, the Parsivel^2's performance was compared to a collocated two-dimensional video disdrometer (Park *et al.*, 2017). The two instruments were in good agreement with respect to droplet size, intensity, kinetic energy and velocity for rainfall rates below approximately 0.4 in./h and drop diameters of 0.02 to 0.16 in. Above 0.8 in./h, the

Figure 3.3 Parsivel^2

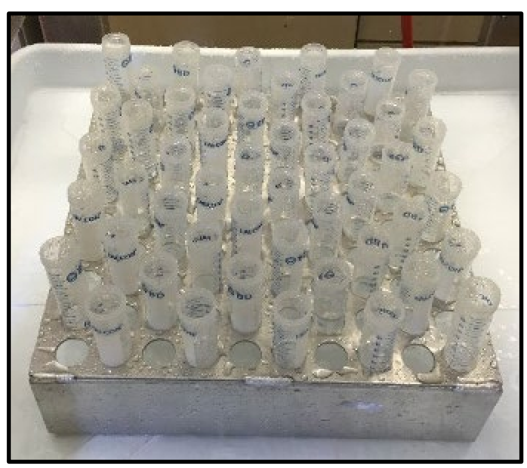

Figure 3.4 Heat map experimental setup

Parsivel^2 overestimated the number of droplets with diameters greater than 0.16 inch, which reinforced the necessity to use multiple measurement techniques when characterizing rainfall. Angulo-Martínez and Barros (2015) have also noted Parsivel^2 measurement errors. However, Raupach and Berne (2015) have demonstrated that it is possible to apply correction factors to Parsivel^2 data to correct for measurement bias, so these data were collected with the intention of applying correction factors in the future. Finally, the spray pattern of the simulator was assessed by creating heat maps of rainfall intensity across the size of the coupons used for experiments. Heat maps were collected by arranging a grid of 50-mL conical tubes spaced 3 in. apart over a 16 in. by 15.5-in. area (Figure 3.4). After a recorded time of rainfall simulation, the volume in each conical tube was measured using a graduated cylinder and converted to an intensity heat map. Some nozzles produced higher intensities toward the middle or sides of the coupons (Figure 3.5) Uniform values were desired for reproducibility of test conditions (Figure 3.6). The shading of the heat maps included in this report were prepared using Microsoft Excel's 2-color scale conditional formatting feature.

TG-1 (x1) @ 20 psi, 50 Diffuser Intensity [in./h]								
0.31	0.31	0.37	0.43	0.43	0.49	0.49	0.49	0.43
0.37	0.37	0.43	0.49	0.61	0.68	0.68	0.61	0.49
0.37	0.31	0.31	0.74	0.86	0.80	0.80	0.80	0.61
0.49	0.61	0.61	1.04	1.17	1.04	1.04	0.86	0.68
0.61	0.80	0.80	1.29	1.41	1.23	1.23	0.98	0.74
0.61	0.92	1.04	1.47	1.47	1.23	1.23	0.98	0.68
0.61	0.92	1.23	1.54	1.54	1.23	1.23	0.86	0.61
0.55	0.86	1.23	1.29	1.35	0.92	0.92	0.74	0.49
0.49	0.86	1.11	0.98	0.98	0.74	0.74	0.55	0.43

Figure 3.5 Example heat map of a nozzle with a non-uniform spray pattern

HH-14WSQ, 5 psi Intensity [in./h]								
0.74	0.74	0.92	0.92	0.92	0.74	0.74	0.74	0.74
0.74	0.92	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74

Figure 3.6 Example heat map of a uniform spray pattern

3.2 10-ft. Tall Rainfall Simulator

From approximately January 2016 to May 2017, a 10-ft tall rainfall simulator was used for washoff experiments (Figure 3.7). The simulator consisted of a manifold with locations for up to five exchangeable misting nozzles mounted at the top of a metal frame enclosed by Plexiglass. The manifold consisted of a 0.25-in. diameter pipe preceded by a pressure reducing valve (Watts® ¾ in. part number LFN45BM1-U, 50 psi). The misting nozzles used throughout this testing period were obtained from McMaster-Carr and Tee-Jet. Although the manifold was designed to accommodate up to five nozzles, only one nozzle (in the center position) was used for most of the characterization testing. Table 3.2 summarizes the average droplet size and intensity parameters for each nozzle at different operating pressures. The "diffuser", as referred to in the table, is an optional insert in the nozzle head and comes in different screen sizes. In general, the operating pressure did not consistently vary the intensity produced by each specific nozzle. Also, different nozzles did not display an appreciable difference in droplet size. More variation in intensity values was achievable by using different combinations of nozzles (ranging from a low of 0.9 in/h to the highest achievable value of 6.5 in/h). However, only the TG-1 nozzle operating at 15 psi produced droplet size and velocity distributions that followed the Gunn-Kinzer reference curve. Obtaining spatial uniformity of intensity over the area of the coupon was also challenging when using the 10-ft. tall simulator. Appendix A contains all the heat maps that were collected. In an effort to produce larger droplet sizes, several simulator characterization tests were conducted using a large mesh screen located several in. below the nozzle outlets (Figure 3.8 and see Table 3.2 notes). In addition to larger visible droplets, the presence of the mesh also resulted in much higher intensity values towards the center of the coupon as compared to the edges (see heat maps marked "mesh" in Appendix A).

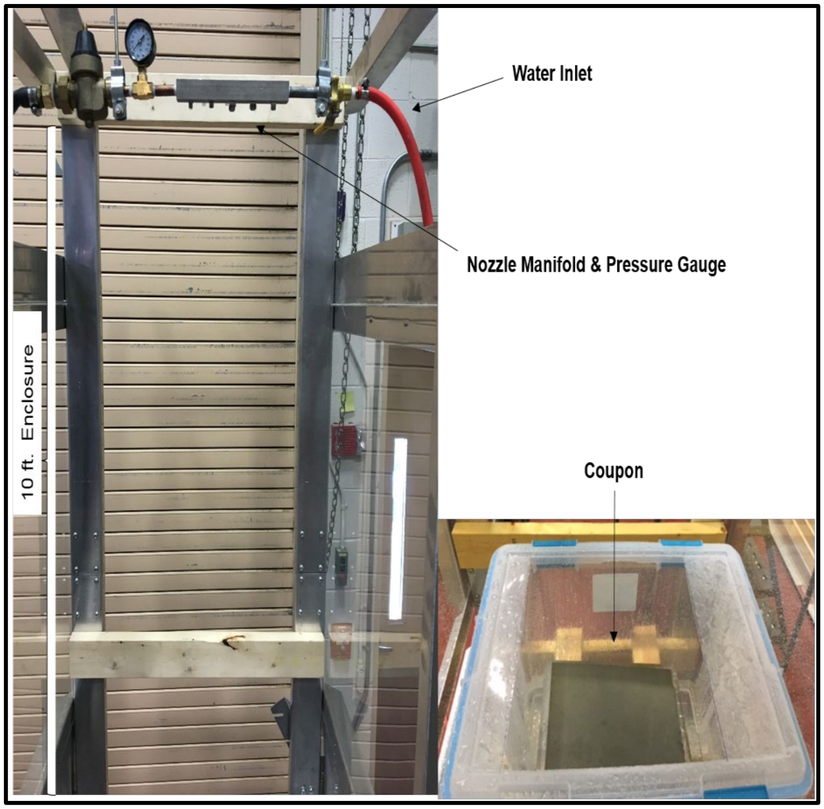

Figure 3.7 10-ft. tall rainfall simulator

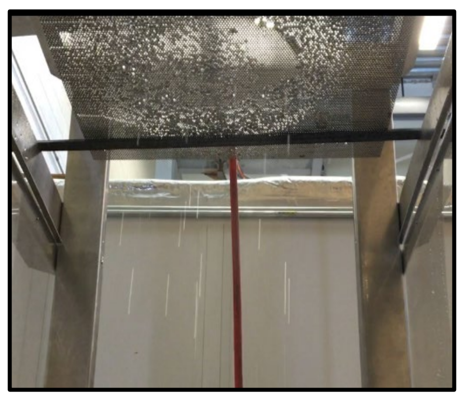

Figure 3.8 10-ft. tall rainfall simulator with mesh screen

Table 3.2. 10-ft. tall rainfall simulator nozzle summary of intensity and droplet size

Nozzle	Diffuser	Heat Map Available	Pressure (psi)	12 in. x 12 in. Bin Intensity (in./h)	Parsivel Intensity (in./h)	Average Droplet size (mm)	Average Kinetic Energy (J/m^2-h)	Notes
TG-1	50	yes	15	1.1	6.2 ± 0.28	1.32 ± 0.01	1782 ± 120	Spray not sufficient to cover 12 in. x12 in. area
		yes	40	1.4	3.6 ± 0.28	0.79 ± 0.01	543 ± 60	-
		yes	90	5.9	3.1 ± 0.59	0.81 ± 0.02	269 ± 63	-
			15	0.5	7.7 ± 0.85	1.43 ± 0.02	2312 ± 316	Parsivel^2 spectograph follows Gunn-Kinzer curve
			40	1.0	5.7 ± 0.24	1.18 ± 0.02	1622 ± 95	-
			90	3.7	3.9 ± 0.47	0.82 ± 0.02	426 ± 53	-
			15	1.7	3.0 ± 0.58	0.98 ± 0.03	1069 ± 287	Mesh under nozzle manifold. Parsivel^2 spectograph follows Gunn-Kinzer curve
		yes	40	2.6	6.0 ± 0.74	0.98 ± 0.06	1783 ± 405	Mesh under nozzle manifold. Generates both mist and large droplets
		yes	90	5.4	7.0 ± 1.38	0.86 ± 0.01	1648 ± 982	Mesh under nozzle manifold. Generates both mist and large droplets
	100	yes	15	1.8	4.9 ± 0.31	1.25 ± 0.01	1339 ± 116	Spray not sufficient to cover 12"x12" area
		yes	40	3.3	3.6 ± 0.26	0.78 ± 0.01	553 ± 86	-
		yes	90	4.8	4.1 ± 0.63	0.86 ± 0.02	366 ± 70	-
FL5-VS	50		15	produced an uneven droplet spray that cannot be accurately quantified				
			40					
			90					
	100		15					
			40					
		yes	90					
SS4.3W	50		15	produced an uneven droplet spray that cannot be accurately quantified				
			40					
			90					
	100		40	1.9	1.4 ± 0.11	0.81 ± 0.01	140 ± 28	-
		yes	40	1.7	0.8 ± 0.08	0.62 ± 0.00	47 ± 6	-
		yes	90	3.7	1.8 ± 0.29	0.95 ± 0.01	209 ± 59	-
			90	5.5	1.4 ± 0.25	0.68 ± 0.02	72 ± 15	-

Table 3.2, continued

Nozzle	Diffuser	Heat Map Available	Pressure (psi)	12 in. x 12 in. Bin Intensity	Parsivel Intensity (in/h)	Average Droplet size (mm)	Average Kinetic Energy	Notes
M3	N/A		40	1.0	0.6 ± 0.10	0.63 ± 0.01	21 ± 5	-
	N/A		90	1.0	0.6 ± 0.09	0.63 ± 0.01	24 ± 4	-
M5	N/A		40	1.0	0.5 ± 0.16	0.62 ± 0.01	17 ± 7	-
	N/A		90	1.0	0.4 ± 0.12	0.61 ± 0.01	17 ± 6	-
M15	N/A		40	2.0	0.9 ± 0.13	0.64 ± 0.01	40 ± 7	-
	N/A		90	2.0	0.7 ± 0.10	0.62 ± 0.01	33 ± 5	-
M1 (x2)	N/A		90	0.9	0.3 ± 0.08	0.62 ± 0.01	12 ± 6	-
M3	N/A	yes	90	1.6	0.1 ± 0.07	0.59 ± 0.01	4 ± 3	-
M1 + M3 + M5	N/A	yes	90	4.4	0.8 ± 0.15	0.70 ± 0.02	42 ± 9	-
M15 (x2) + M5	N/A	yes	90	6.5	1.0 ± 0.17	0.74 ± 0.03	60 ± 8	-

Nozzle Part Numbers: M1 = McMaster-Carr 3178K61; M3 = McMaster-Carr 3178K63; M5 = McMaster-Carr 3178K75; M15 = McMaster-Carr 3178K77; TG-1 = TeeJet; FL5-VS = TeeJet; SS4.3W = TeeJet

A total of 16 washoff experiments were conducted using the 10-ft. rainfall simulator and *Bg* spores (a simulant for *Ba*), aerosol-deposited onto a 12-in. by 12-in. concrete coupon (Figure 3.9). Appendix B outlines the procedure for performing rainfall washoff experiments. Four intensities (0.5, 1, 3, and 6 in./h) were determined using only the collection bin method. This method corresponded to two M1 nozzles for the 0.5 in./h event, one M3 nozzle for the 1 in./h, M1, M3, and M5 nozzles for the 3 in./h event, and two M15 and one M5 nozzle for the 6 in./h event, all operated at 90 psi. The Parsivel[2] had not been procured by this point in the project, so measurements collected in Table 3.2 were taken as replicates post-experiment, not from the same day as the test. Known discrepancies between the measured data for intensity on the day of the test and upon re-evaluation warrant caution in interpreting the data for intensity patterns. Duplicate tests were run at each intensity value, and the mesh was used to produce larger droplets under the set of experiments in Figure 3.6 A. Appendix C contains the raw data from these runoff experiments.

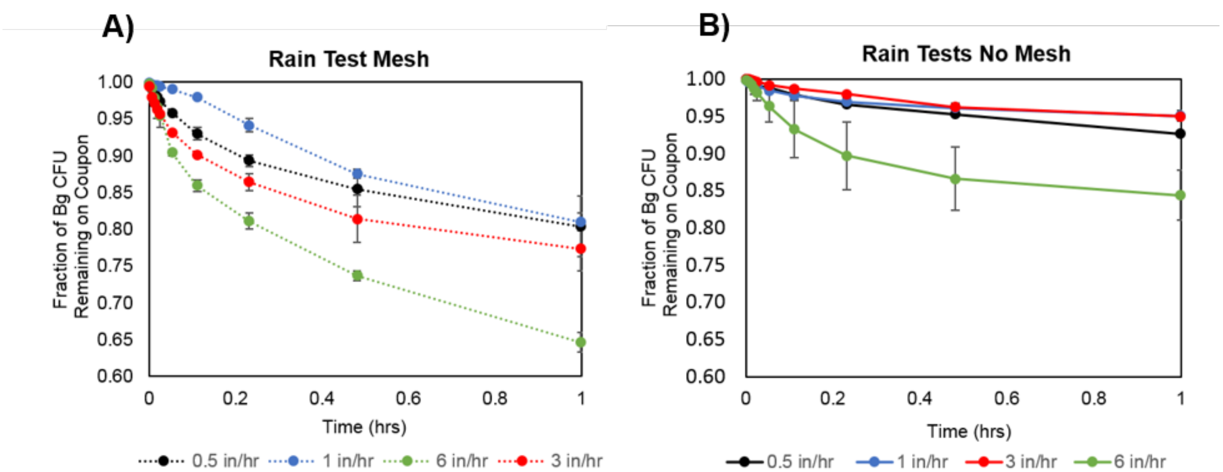

Figure 3.9 10-ft simulator rainfall removal results (for *Bg*) at different intensity rain events. A) Experiments using a mesh screen below the nozzle manifold. B) Experiments without the mesh. Error bars represent standard error for duplicate experimental conditions.

In Spring of 2017, we decided to redesign the simulator for several reasons. First, the 10-ft. simulator consistently had poor agreement between the intensities calculated using the bin, the Parsivel[2], and the heat map methods. While some of this lack of agreement could be explained by the known measurement errors for the Parsivel[2] (see discussion in section 3.1), it was also challenging to obtain repeatable spray patterns (and as a result, intensities) for the nozzles tested. This was due to the nozzle's cone of spray varying in intensity across the size of the coupons and thus relying on the coupon to be placed at exactly in the same position under the manifold each test. Further, only a few operating pressure/nozzle conditions resulted in droplet velocities that followed the Gunn-Kinzer curve. The next generation of rainfall simulator was designed to be both taller (to afford the droplets more time to reach terminal velocity), and different nozzles were tested for a more consistent spray pattern.

3.3 26-ft. Tall Rainfall Simulator

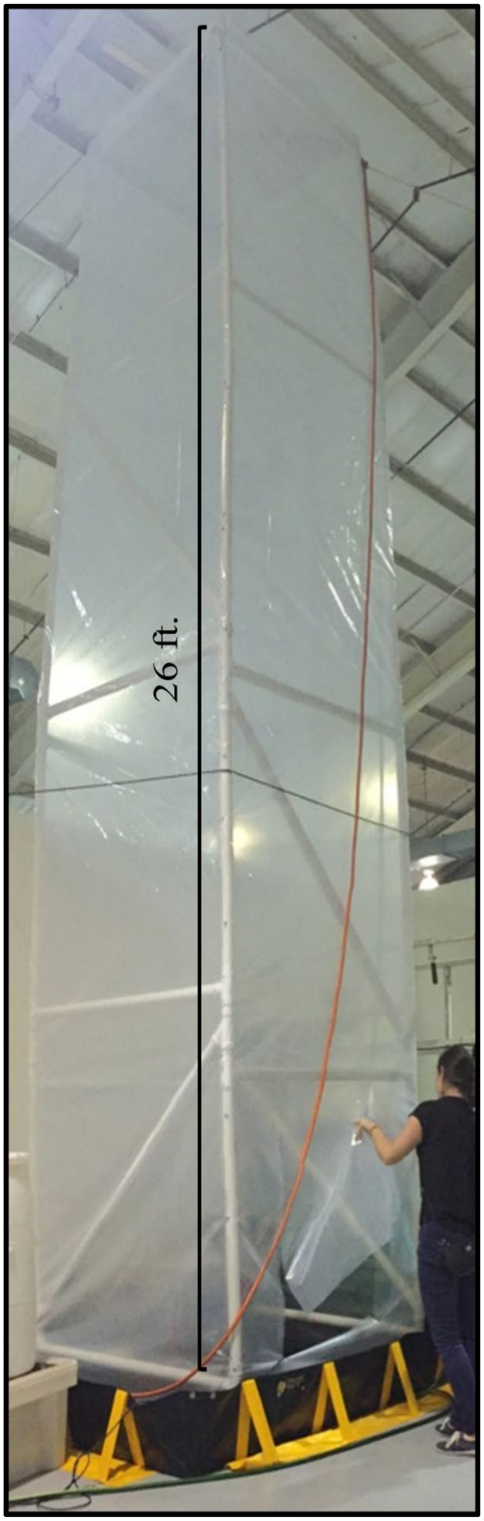

Figure 3.10 26-ft tall rainfall simulator

During the Summer of 2017, a 26-ft. tall rainfall simulator was designed and constructed at the EPA's Fluid Modeling Facility in Research Triangle Park (RTP), North Carolina (Figure 3.10). 26-ft was the tallest height that could be accommodated in an indoor facility on campus (a higher height, in theory, helped more droplets reach terminal velocity). The structure was composed of a polyvinyl chloride (PVC) pipe frame with an approximately 5-ft. by 5-ft. footprint. The sides of the structure were encased with thick plastic sheeting to prevent water from spraying outside a water containment basin. The 26-ft tall simulator was built with direct plumbing to a deionized water source and a 400-gallon and a 35-gallon deionized water reservoir next to the structure. A ¾- horsepower general purpose motorized pump with pressure gauge was used to supply water via a hose to the top of the simulator. The nozzle manifold located at the top-center of the structure was repurposed from the 10-ft. simulator. The manifold has a capacity to hold up to five nozzles and has an inlet pressure gauge with an operating pressure range of 5-100 psi. Additional accessories for the work area included a computer work station for operation of the Parsivel^2, an area dedicated to personal protective equipment (harnesses, hardhats, gloves, and laboratory coats) and a scissor lift for maintenance and changing nozzles. Coupon holders were also redesigned to minimize collection of water droplets that did not hit the coupon. The coupon holders consisted of stainless-steel exteriors with plastic molds on the interiors to snugly fit concrete and asphalt coupons (Figure 3.11). In the same manner as the 10-ft. tall simulator, the 26-ft. simulator was characterized for uniformity of the spray distribution using heat maps (Appendix D). Table 3.3 summarizes the average droplet size and intensity parameters for each nozzle at different operating pressures.

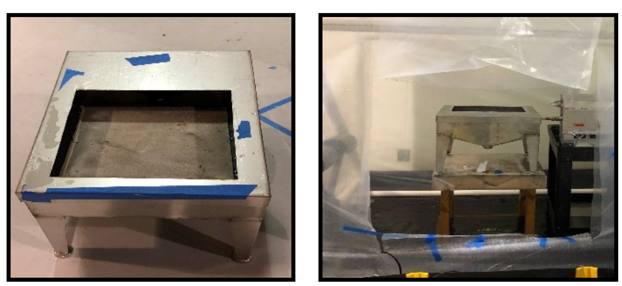

Figure 3.11 Washoff coupon holders

Table 3.3 26-ft. tall rainfall simulator nozzle summary of intensity and droplet size

Nozzle	Diffuser	Heat Map Available	Pressure (psi)	12 in. x12 in. Bin Intensity (in./h)	Parsivel Intensity (in./h)	Average Droplet Size (mm)	Kinetic Energy (J/m^2-h)	Notes
TG-1	50	yes	20	0.935	0.73 ± 0.16	0.93 ± 0.11	207.6 ± 54.77	Follows Gunn-Kinzer curve. One hour heatmap is hotter towards the center, not an even distribution.
TG-1 (x2)	50	yes (1 hour and 22 min.)	20	3.354	2.38 ± 0.57	0.73 ± 0.04	159 ± 40.03	Does not follow Gunn-Kinzer curve. One hour heatmap is hotter towards bottom right.
FL5-VS	50	yes	40	1.829	0.545 ± 0.083	0.61 ± 0.01	20.50 ± 4.55	Does not follow the Gunn-Kinzer curve. Droplets are small. Heat map was collected over one hour.
	50	yes	50	0.772	0.55 ± 0.03	0.61 ± 0.01	54.52 ± 6.33	Follows Gunn-Kinzer curve but most droplets are small with few large ones falling under the curve. Heat map was collected over one hour.
FL5-VS (x2)	50	yes	50	1.911	0.74 ± 0.16	0.63 ± 0.01	37.68 ± 24.66	Gunn-Kinzer curve looks very blocky. Heat map was collected over one hour.
HH-6SQ	NA	yes (1 hour and 20 min.)	5	4.512	2.14 ± 0.29	0.69 ± 0.07	320.76 ± 49.91	Follows Gunn-Kinzer curve. The heat map showed rainfall not as evenly distributed during the 20 minute duration test
HH-14WSQ	NA	yes	5	0.671	0.45 ± 0.04	0.63 ± 0.01	82.73 ± 17.21	Follows Gunn-Kinzer curve and heat map shows even distribution of the droplets.
	NA	yes	5	0.640	0.418 ± 0.04	0.63 ± 0.01	80.18 ± 17.05	Follows Gunn-Kinzer curve and heat map shows even distribution of the droplets.
HH-30WSQ	NA	yes	5	2.859	1.769 ± 0.16	0.71 ± 0.01	553.28 ± 118.28	Follow Gunn-Kinzer curve and heat map shows even distribution of the droplets
HH-50WSQ	NA	yes	5	4.024	2.53 ± 0.57	0.77 ± 0.02	1475.43 ± 825	Follows Gunn-Kinzer curve and heat map shows even distribution of the droplets. Larger particles than previously observed produced as well.

Table 3.3., continued

Nozzle	Diffuser	Heat Map Available	Pressure (psi)	12 in. x12 in. Bin Intensity (in./h)	Parsivel Intensity (in./h)	Average Droplet Size (mm)	Kinetic Energy (J/m^2-h)	Notes
HH-1	NA	yes iteration 1	5	3.598	3.39 ± 0.59	0.76 ± 0.24	1475.43 ± 825	Follows Gunn-Kinzer curve. Heat map off center.
	NA	yes iteration 2	5	1.585	1.58 ± 0.26	0.67 ± 0.01	192.70 ± 37.16	Follows Gunn-Kinzer curve, but blocky.
	NA	yes iteration 3	5	1.460	1.26 ± 0.162	0.63 ± 0.01	132.99 ± 18.21	Follows Gunn-Kinzer curve. Heat map slightly off center.
	NA	yes iteration 4	5	1.280	1.29 ± 0.16	0.64 ± 0.01	142.23 ± 14.69	Follows Gunn-Kinzer curve. Heat map slightly off center.
	NA	yes	20	3.170	1.60 ± 0.25	0.66 ± 0.02	27.74 ± 18.80	Does not follow Gunn-Kinzer curve. Heat map off center.
HH-1 (x2)	NA	yes	5	1.950	1.73 ± 0.15	0.67 ± 0.01	240.27 ± 20.73	Follows Gunn-Kinzer curve and has higher droplets counts. Flowrate drops after first nozzle, second nozzle not receiving the same flowrate.
GG-1.5W	NA	yes	5	1.646	1.72 ± 0.27	0.67 ± 0.02	220.95 ± 33.75	Follows Gunn-Kinzer curve, slightly blocky. Heat map slightly off from center.
GG-2.8W	NA	yes	5	0.915	0.58 ± 0.04	0.58 ± 0.01	52.05 ± 6.52	Follows Gunn-Kinzer curve. Heat map very evenly distributed

Nozzle Suppliers: Tee-Jet (TG-1, FL5-VS); Spraying Systems Co., iSpray (HH-6SQ, HH-14WSQ, HH-30WSQ, HH-50WSQ, HH-1, GG-1.5W, GG-2.8W)

The notes in Table 3.3 indicate that the redesign of the simulator made a marked difference in achieving the design goals of the apparatus. With the additional height, all nozzles, excluding TG-1 (x2) and FL5-VS at 40 psi, achieved droplet size-velocity combinations that followed the Gunn-Kinzer curve for natural rain. Ultimately, the final nozzles were selected based upon having heat maps that demonstrated a uniform spray pattern (see Figure 3.6 for example of a uniform spray pattern). The nozzles that fit this criterion were HH-1, HH-14WSQ, HH-30WSQ, HH-50WSQ, and GG-2.8W. These nozzles allowed for an intensity range for the 26-ft. simulator of approximately 0.66 in/h to 4 in/h, which were also in line with the original design goals.

As of the date of publication, a total of 32 washoff experiments have been conducted using the 26-ft. rainfall simulator. *Bg* and *Btk* aerosol spores were deposited onto 12-in. by 12-in. concrete and asphalt coupons and measured in the runoff water using standard microbiological plating methods. *Bg* is traditionally used as a *Ba* simulant for disinfection research and *Btk* for aerosol fate and transport research. Both microorganisms are being tested in this stormwater research for applicability to historical results from both microorganisms. Appendix E contains the raw data and rainfall conditions from these runoff experiments. Their analysis will be the subject of future publications.

4.0 Channelized Flow

A channelized flow simulator was designed to study how spores are removed by sheet flow that occurs on roads and curbs. The simulator was designed and built from half-inch Plexiglass and with adjustable feet. The simulator contained a recessed trough for a 14-in. by 14-in. coupon (1-in.-thick) to be mounted at a 5% slope (Figure 4.1). During experiments, concrete coupons were sealed in place to prevent short circuiting. Water was first pumped into a reservoir using an adjustable pressure gauge, which then flowed over an aluminum foil-covered spillway before flowing over the concrete surface. The aluminum foil helped to maintain sheet flow. Sheet flow was achieved for flowrates of 25 mL/s to 150 mL/s. The simulator contained a removal collection basin at the outlet orifice to allow for collection of runoff water contaminated with spores. Appendix F contains a detailed procedure for runoff experiments.

A total of 9 experiments were conducted using the channelized flow simulator (one at 25 mL/s,

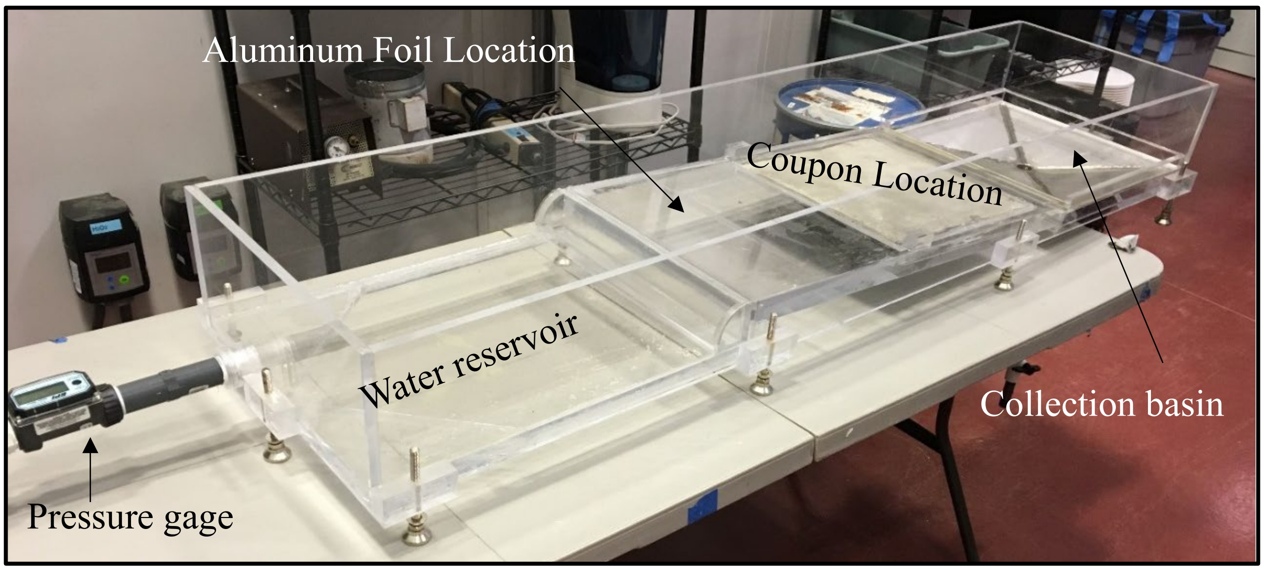

Figure 4.1 Custom Channelized Flow Simulator

and two each at 50 mL/s, 75 mL/s, 100 mL/s, and 150 mL/s). Appendix G contains the raw data (spore counts in collected runoff water) from the experiments shown in Figure 4.2. At the one-hour time point, more spores were not necessarily removed by higher flow rates (e.g., 75 mL/s removed more spores than 100 mL/s or 150 mL/s). As indicated by the error bars in Figure 4.2, there was also variability in the spore removal between tests conducted at the same flow rate. Since water velocity is a key determinant for inducing movement in river sediment, the channelized flow simulator was also carefully analyzed for velocity at each of the flow rates used during the experiments. For the velocity assessment, height of water was measured above each coupon using a point gauge. The slope of the coupon was accounted for in the calculations. Velocity was calculated using both volumetric and Manning's Equation approaches (Table 4.1) (Mays, 2010). Appendix H contains the raw depth of water data and the equations used to make the calculations in Table 4.1. The result of the analysis indicates that all experiments were conducted at similar velocities (i.e., as flow rate increased, so did the water depth, but not water velocity). These initial results suggest that spore removal is variable within the same velocity range and may be controlled by other factors such as surface roughness of the material. Another explanation for the variability is that the velocity that was used (average 0.27 m/s) is near to the velocity that the Shields diagram predicts is the threshold of motion for particles in the size range of spores near 0.18 m/s. Rather than proceed to other urban material coupons (e.g., asphalt or brick) or spore types, we decided to procure a channel manufactured with more precision to test spore removal at a range of velocities, both definitively above and below the theoretical value for the threshold of motion. In future experiments, a sediment demonstration channel (Armfield, Inc., Clarksburg, New Jersey, USA) with length 1.55 m, width 0.78 m, and depth 0.11 m, an adjustable 0-10% slope, flow rates between 0.2-0.6 liters (L)/s, and an adjustable weir at the outlet of the channel will be used to better understand the removal of spores (by colony forming units [CFUs]) in channelized streams of water.

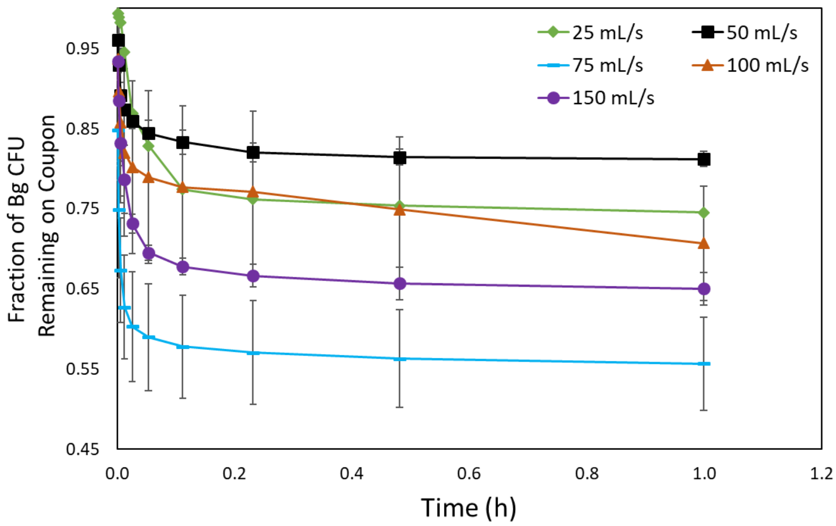

Figure 4.2 Channelized flow *Bg* washoff from concrete coupon. Error bars are standard error.

Table 4.1 Velocities during channelized flow experiments

Whole Coupon Parameters (using average height)						
Flowrate	**Average Water Height (in)**	**Water Height Stdev (in)**	**Volumetric Velocity (m/s)**	**Volumetric Velocity Stdev (m/s)**	**Manning Velocity (m/s)**	**Manning Velocity Stdev (m/s)**
50	0.063	0.019	0.262	0.393	0.341	0.065
75	0.054	0.018	0.306	1.165	0.304	0.071
100	0.063	0.016	0.264	0.322	0.335	0.057
150	0.071	0.024	0.235	0.342	0.362	0.095

5.0 Spray-Down

A chamber was used to evaluate the effect of sprayed water on the removal of spores from concrete, brick, asphalt, and glass. Coupons were inoculated with spores using an aerosolized deposition approach and spores were measured in the spray runoff water. A stainless-steel chamber (40 in. (L) x 38 in. (W) x 36 in. (H), with an acrylic hinged front door was used for a controlled environment (Figure 5.1). The top of the chamber included ports through which the test materials were sprayed. The chamber also contained a sloped basin that led to an outlet port for sample collection. A horizontal load cell was used to record the mass (pounds) applied to the material. Coupons were cut to 5.5-in. × 5.5-in. to match the load cell dimensions and allowed the force reading to be representative of the water hitting the coupon. The water delivery system consisted of a conventional garden hose–type bore nozzle (40 psi, with dial that could switch among seven different spray patterns) and a pressure washer rated at 1600 psi with adjustable slit nozzles. All garden hose nozzles produced a spray that would cover the entire test coupon, but the pressure washer nozzle tips did not necessarily cover the coupon. Each pressure washer nozzle type was tested at different distances from the coupon surface to determine when the entire coupon was covered by the spray (Table 5.1). In Table 5.1, different pressure washer nozzles are identified according to the spray angle (in degrees). These designations come predetermined by the manufacturer. “Height” in Table 5.1 refers to the distance the nozzle was held from the surface of the horizontal surface. “Length” and “width” refer to the measured spray area that was produced on the horizontal surface at the height and nozzle condition.

Figure 5.1 Spray Chamber

Table 5.1 Pressure washer nozzle spray conditions

Nozzle (°)	Height (ft)	Length (in)	Width (in)	Approximate Area (in^2)	Notes
0	1	3.25	3.25	8.30	All sprays are approximately radial since it is formed through the perpendicular impact of the water jet against the concrete surface.
	2	4.6	4.6	16.62	
	3	5.5	5.5	23.76	
	4	6	6	28.27	
	5	7.125	7.125	39.87	
	6	7.5	7.5	44.18	
15	1	7	7.25	41.28	All of the widths are generated through splashing, and therefore approximations. Variance in the width is affected by unnacounted variables including wind, slant of the surface, and measurement technique. In some cases, the center did not seem to get sprayed with water as much. In instances where the center did not have the largest width, then the centermost largest area width was taken.
	2	8.25	9	63.62	
	3	12	9	169.65	
	4	14.25	11	246.22	
	5	13.625	9	192.62	
	6	16	7	175.93	
25	1	9	7.5	106.03	
	2	10.5	6.5	107.21	
	3	13	7.125	145.49	
	4	19	8	238.76	
	5	21.125	8.5	282.06	
	6	22.5	8.5	300.41	
40	1	11.75	4.875	89.98	
	2	18.375	5.875	169.57	
	3	21.5	6	202.63	
	4	25.25	6	237.98	
	5	33.5	6	315.73	
	6	43	7	472.81	

Using information from Table 5.1, we decided to operate both the pressure washer and garden hose at a distance of 34 in. from nozzle tip to coupon surface which ensured the entire coupon was covered by the spray regardless of which spray nozzle was used.

Mass of water applied was recorded over time for both the garden hose (Figure 5.2) and the pressure washer (Figure 5.3) to test the responsiveness of the load cell. From these data, a duration of five seconds was selected for the application of the water spray. This time was selected to allow the load cell sufficient time to respond. The time was also an operationally feasible duration to reproduce. The 15-degree nozzle was selected for the pressure washer, and the shower spray setting was selected for the garden hose (from options of center, cone, flat, full, or shower) to represent an approximate order of magnitude difference in terms of force applied to the coupon.

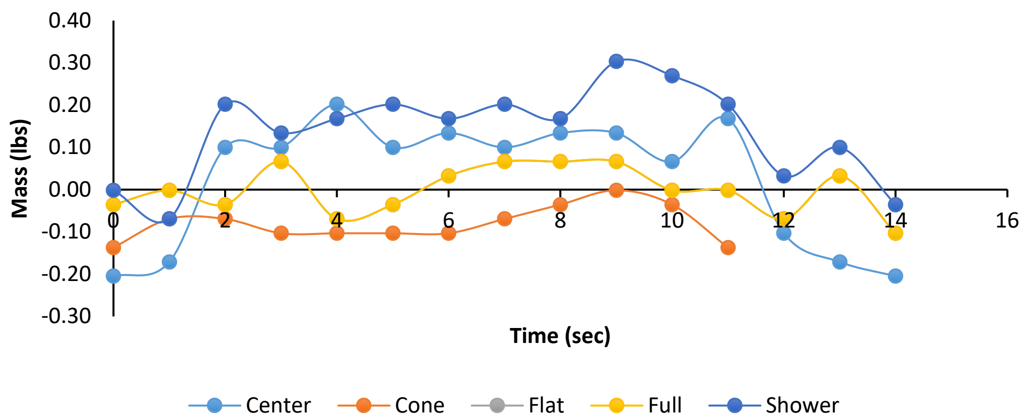

Figure 5.2 Load cell response to different garden hose nozzle tips

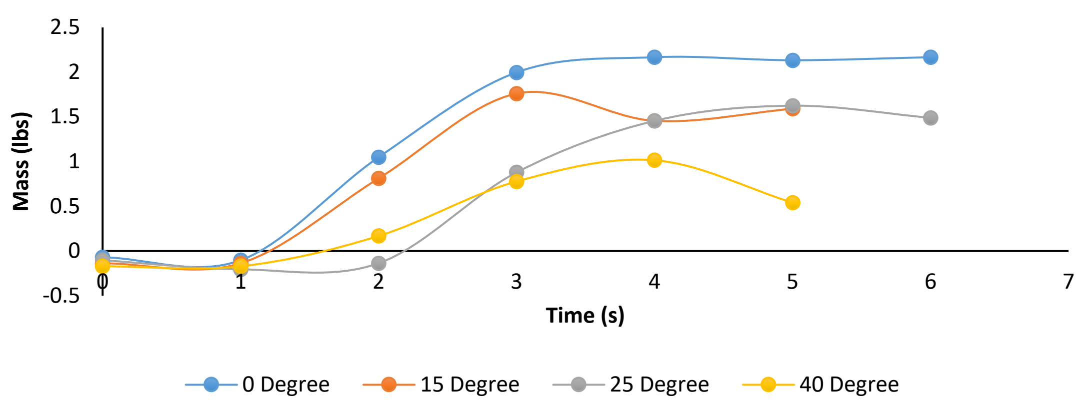

Figure 5.3 Load cell response to different pressure washer nozzle tips

During spray down experiments, first uninoculated coupons (procedural blanks) and then inoculated coupons (test coupons) were mounted in the chamber and sprayed with deionized water with the runoff water collected and analyzed for spores. Appendix I contains a detailed procedure and Appendix J contains results of the tests conducted. As of publication, *Bg* spore removal data have been collected for both the garden hose and pressure washer from concrete, brick, asphalt, and glass. At most 15% of spores were removed from the coupons (Appendix J). The garden hose was just as effective as the pressure washer. Testing to determine the removal of *Btk* spores is still underway.

6.0 Quality Assurance

This project used thermometers, stopwatches, micropipettes, scales, pressure gauges, a pH meter, and a graduated cylinder, calibrated per specifications in Table 6.1.

Table 6.1 Instrument Calibration Frequency

Equipment	Calibration/Certification	Expected Tolerance
Thermometer	Compare to independent NIST thermometer (a thermometer that is recertified annually by either NIST or an ISO-17025 facility) value once per quarter.	±1 °C
Stopwatch	Compare to official U.S. time @ time.gov every 30 days.	± 1 min/30 days
Micropipettes	Certified as calibrated at time of use. Recalibrated by gravimetric evaluation of performance to manufacturer's specifications every year.	± 5 %
Scale	Compare reading to Class S weights every day.	± 1 %
Meter box (pressure gauge)	Volume of gas is compared to NIST-traceable dry gas meter annually.	± 2 %
pH meter	2-point calibration using NIST-traceable buffer solutions immediately prior to testing	± 0.1 pH units
Graduated cylinder	Collection of effluent at specified time.	± 1 mL

NIST = National Institute of Standards and Technology; ISO = International Organization for Standardization

The following measurements were deemed critical to accomplishing part or all of the project objectives: sampling time, sample volume, incubation temperature, count of CFUs, plated volume, rain rate, and overland flow rate. Data quality indicators (DQIs) for the critical measurements were used to determine if the collected data met the project objectives. The critical measurement acceptance criteria are shown in Table 6.2. If the CFU count for bacterial growth does not fall within the target range, the sample will either be filtered or re-plated. Data shown in the appendices of this report met the acceptance criteria in Table 6.2.

Table 6.2 Critical Measurement Acceptance Criteria

Critical Measurement	Measurement Device	Accuracy/Precision Target	Detection Limit
Time	± 1 min/30 days	± 1 min/30 days	NA
Temperature of incubation chamber	NIST-traceable thermometer (daily)	± 2 °C	N/A
Counts of CFU	QCount	Check of spiral plater template that is within 1.82×10^4–2.30×10^4	1 CFU per plate
Plated volume	Spiral plater	50 % relative standard deviation among the triplicate plating	1 CFU
Collection of effluent at specified time	Graduated cylinder	± 1 mL	NA
Collection of effluent over time	Graduated cylinder and NIST-calibrated stopwatch	± 5 % of target set point	NA
Rain and overland flow rate	Graduated cylinder and NIST-calibrated stopwatch	± 5 % of target set point	NA

Quantitative standards do not exist for biological agents. Quantitative determinations of organisms in this investigation did not involve the use of analytical measurement devices. Rather, the CFU were enumerated using a QCount (Advanced Instruments, Norwood, MA, USA) and recorded. Critical QA/QC checks for the biological results are shown in Table 6-3. Controls and blanks were included along with the test samples in the experiments so that well-controlled quantitative values were obtained. Verifying the sterility of samples prior to inoculation and other background checks were also included as part of the standard protocol of each experiment. Replicate coupons were also included for each set of test conditions and the following additional types of quality control samples:

- **Metered dose inhaler (MDI) control coupons:** stainless steel coupons inoculated at the same time as material coupons and sampled by sponge wipe. These coupons are inoculated at the beginning, middle, and end of each inoculation campaign to assess the stability of the MDI during the inoculation operation.
- **Procedural blank coupons:** sterile coupons that undergo the same sampling process as the test coupons.
- **Positive control coupons:** representative material coupons that are inoculated and sampled using a wipe sampling technique.

Additionally, a chain of custody form was used when transferring samples from the simulators to the onsite microbiology laboratory, and a laboratory notebook and an electronic file repository were maintained. During 2017, this project underwent a laboratory control audit by an external reviewer and a technical systems audit by NHSRC’s quality assurance officers. No substantial issues were detected during these audits.

Table 6.3 QA/QC Sample Acceptance Criteria

QC Sample	Information Provided	Frequency	Acceptance Criteria	Corrective Action
Procedural blank (coupon without biological agent).	Controls for sterility of materials and methods used in the procedure.	1 per test.	No observed CFU.	Reject results of test coupons on the same order of magnitude. Identify and remove contamination source.
Positive control (sample from material coupon contaminated with biological agent but not subjected to test conditions).	Initial contamination level on the coupons; allows for determination of log reduction; controls for confounds arising from history impacting bioactivity; controls for special causes; shows plate's ability to support growth.	3 or more replicates per test.	For high inoculation, target loading of 1 x 10^7 CFU per sample with a standard deviation of < 0.5 log (5 x 10^6 – 5 x 10^7 CFU/sample).	Outside target range: discuss potential impact on results with WACOR; correct loading procedure for next test and repeat depending on decided impact. Outlier: evaluate/exclude value.
Blank plating of microbiological supplies.	Controls for sterility of supplies used in dilution plating.	3 of each supply per plating event.	No observed growth following incubation.	Sterilize or dispose of contamination source. Re-plate samples.
Blank TSA sterility control (plate incubated but not inoculated).	Controls for sterility of plates.	Each plate is incubated at least 18 but fewer than 24 hours.	No observed growth following incubation.	All plates are incubated prior to use. All contaminated plates will be discarded.
Procedural blank samples.	Contamination level present during sampling.	1 per sampling event.	Non-detect.	Clean up environment. Sterilize sampling materials before use.
Replicates of microbiological dilution plates.	Repeatability of results.	3 per dilution.	Counts greater than 20 are reportable. Standard deviation must be < 100 %. Grubbs outlier test or equivalent.	Sample will be re-plated.
MDI control (wipe sample from stainless steel coupon contaminated with biological agent).	Initial contamination level on coupons. Shows plate's ability to support growth.	3 replicates per MDI use.	Target loading CFU per sample with a standard deviation of < 0.5 log. No evidence of MDI decay during inoculation event. Grubbs outlier test (or equivalent).	Outside target range: discuss potential impact on results with WACOR; correct loading procedure for next test and repeat depending on decided impact. Outlier: evaluate stability of MDIs.
Pressure of hose	Pressure impacts flow rate and spray pattern	Per use	41–46 psi	Correct pressure according to manufacturer's directions; replace if problem cannot be resolved

7.0 Future Work

Decision makers need data and maps to help determine if evacuation zones need to be shifted, what portions of their infrastructure should be cleaned, where they should situation waste and how this could change after different sized rain events. Washoff data collection provides not only a rough understanding of how "sticky" a certain contaminant is, but can also be used to develop mathematical models that power simulations. The laboratory capabilities described in this report are tools that can be used on most contaminants of concern and expanded upon to answer specific questions about certain hydraulic conditions.

The 26-ft. tall rainfall simulator will continue to be used to study spore washoff by different simulated rain events. Now that its nozzles are well-characterized and produce realistic rain events for a constant duration intensity, we plan to investigate washoff from rain events with different patterns of intensity and drying. We also plan to explore the influence of stormwater quality on the adhesion of both types of simulants. These experiments will have additions of natural organic matter and metals (e.g. copper and zinc) to the water. The rainfall simulator is available for washoff studies of chemical and radiological (with safety enhancements) particulates in addition to biological. A related effort within NHSRC has involved building a physical model of a portion of a city. The rainfall simulator may be used to simulate storm events to verify hydraulic models. Ultimately, the washoff curves produced with this simulator will be used to inform parameterization of stormwater models so that the movement of spores and other contaminants during rain events may be translated into maps used by emergency responders and decision makers for sampling, public health decisions, and remediation. These mapping activities can be combined with other mapping products (e.g., transportation logistics, affected infrastructure) to allow decision makers to make their decisions based on a situational awareness of the complex system of systems that are in play during a wide-area response.

The channelized flow experiments will be repeated using *Bg* and *Btk* in the Armfield sediment channel to better understand the velocity conditions that induce movement of spores and to understand the interplay between material type and movement of spores. Velocity will become a critical measurement instead of flow for these experiments. Eventually this channel may also be used to study the fate and transport of spores and other contaminants in river systems.

Finally, the pressure washing laboratory experiments will be completed using *Btk* spores, and outdoor tests are being planned to compare to the laboratory results for removal efficacy. Initial outdoor scoping tests using a pressure washer indicate that it is difficult to generate large enough volumes of runoff water to collect the spores that have been dislodged. Outdoor tests will seek to operationalize a rinse procedure that generates collectable volumes of water. Surfactants will also be considered as wash aids.

8.0 References

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Appendix A. 10-ft. Intensity Heat Maps

* Refer to Section 3.1 in the body of the report for an explanation how these data were generated and their significance.

M3 @ 90 psi Intensity [in./h]								
0.92	1.11	1.29	1.57	1.66	1.66	1.66	1.29	1.29
1.11	1.29	1.47	1.66	1.84	2.21	2.03	1.93	1.47
1.11	1.29	1.47	1.84	2.21	2.58	2.40	2.21	1.66
1.11	1.20	1.47	1.84	2.40	2.40	2.76	2.40	2.03
0.92	1.11	1.29	1.84	2.21	2.40	2.58	2.40	2.03
0.74	1.11	1.29	1.66	2.03	2.21	2.40	2.21	1.84
0.74	0.92	1.11	1.29	1.66	1.84	2.03	1.84	1.66
0.55	0.74	0.74	0.92	1.29	1.47	1.66	1.47	1.11
0.37	0.55	0.74	0.74	1.29	1.11	1.11	0.92	0.74

M1 @ 90 psi Intensity [in./h]								
0.37	0.55	0.55	0.55	0.55	0.74	0.55	0.55	0.55
0.55	0.55	0.55	0.74	0.74	0.92	0.74	0.74	0.74
0.55	0.74	0.74	1.11	1.11	1.11	1.11	1.11	1.11
0.55	0.74	0.92	1.20	1.47	1.47	1.47	1.47	1.29
0.74	0.92	1.20	1.47	1.47	1.66	1.66	1.66	1.47
0.55	0.92	1.29	1.47	1.47	1.66	1.66	1.66	1.47
0.55	0.74	0.92	1.29	1.47	1.47	1.47	1.47	1.29
0.46	0.55	0.74	0.92	1.11	1.11	1.11	1.11	0.92
0.09	0.46	0.55	0.64	0.55	0.92	0.74	0.74	0.64

M1+M3+M5 @ 90 psi Intensity [in./h]								
3.32	3.87	4.79	4.79	5.71	5.53	5.16	4.61	3.50
4.79	5.34	6.08	6.45	7.19	6.82	5.90	4.98	4.24
6.27	6.82	7.00	7.92	8.29	7.55	6.45	5.53	4.42
6.63	7.74	7.92	8.48	8.11	6.63	5.90	4.98	4.42
5.71	6.45	7.19	7.00	6.27	5.34	4.79	4.24	3.50
4.79	5.53	5.16	5.34	4.79	4.24	3.87	3.32	2.95
3.50	3.87	3.69	3.87	3.69	3.13	2.76	2.40	2.58
2.03	2.76	2.76	2.58	2.58	2.58	2.21	2.21	1.84
1.84	2.03	2.03	2.21	1.84	2.03	1.84	1.29	1.47

2 M15 + 1 M5 @ 90 psi Intensity [in./h]								
7.37	7.37	7.62	6.88	6.39	6.14	5.90	5.65	5.41
8.35	7.37	7.12	6.63	6.39	5.90	5.16	5.16	5.16
8.84	8.11	7.62	6.63	6.14	5.65	5.41	5.16	5.16
9.09	9.34	7.86	7.37	6.39	5.90	5.41	5.16	5.16
9.83	10.56	9.34	7.62	7.12	5.90	5.41	6.14	5.65
9.83	10.32	10.56	9.58	8.11	7.37	6.39	5.90	5.90
9.34	11.06	11.30	10.56	9.58	8.11	7.37	6.88	6.39
8.11	9.58	11.06	11.06	10.07	8.84	8.35	7.37	7.37
6.88	8.11	8.84	9.58	9.34	9.09	8.35	8.11	7.62

TG-1 @ 15 psi & 50 Diffuser Intensity [in./h]								
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.09	0.09	0.00	0.00	0.00	0.00
0.00	0.00	0.09	2.58	2.58	0.18	0.00	0.00	0.00
0.00	0.00	0.37	10.50	10.50	0.55	0.00	0.00	0.00
0.00	0.00	0.00	0.74	0.74	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TG-1 @ 40 psi and 50 Diffuser Intensity [in./h]								
0.37	0.46	0.55	0.37	0.37	0.18	0.00	0.00	0.00
0.55	0.74	0.92	1.11	0.92	0.55	0.37	0.18	0.09
0.92	1.29	2.40	2.95	2.76	1.66	0.83	0.37	0.09
1.20	2.58	4.98	6.82	6.63	3.87	1.47	0.55	0.18
1.66	4.24	7.55	9.58	10.13	5.90	2.40	0.92	0.37
1.47	4.24	8.84	10.69	9.40	5.90	2.40	0.92	0.55
1.29	3.13	6.63	7.74	6.45	4.24	2.03	0.74	0.55
0.74	1.66	3.13	4.42	3.87	2.58	1.38	0.74	0.55
0.37	0.55	1.29	1.66	1.66	1.29	0.92	0.74	0.55

TG-1 @ 40 psi and 50 Diffuser and Mesh on Simulator Intensity [in./h]								
0.00	0.00	0.18	0.37	0.55	0.37	0.18	0.00	0.00
0.18	0.37	0.37	0.55	0.64	0.55	0.55	0.37	0.18
0.37	0.55	0.55	0.92	1.29	1.11	0.92	0.55	0.37
0.46	0.74	1.11	2.03	2.21	3.32	1.47	0.74	0.55
0.92	1.11	1.84	8.84	6.08	7.19	2.40	1.11	0.92
0.55	1.11	1.66	6.45	6.82	7.92	2.21	0.92	0.55
0.55	0.92	1.29	2.03	2.21	2.03	1.29	0.74	0.55
0.37	0.55	0.74	1.11	1.29	1.11	0.74	0.55	0.37
0.18	0.37	0.55	0.55	0.74	0.55	0.55	0.37	0.00

TG-1 @ 90 psi and 50 Diffuser Intensity [in./h]								
1.25	1.41	1.88	1.88	2.04	1.73	1.41	0.94	0.63
1.73	2.35	2.82	3.29	3.14	2.51	1.88	1.25	0.78
2.35	3.45	4.55	5.18	4.94	3.92	2.67	1.41	0.78
2.98	4.86	6.90	8.31	6.90	5.18	3.14	1.73	0.94
3.76	6.59	8.94	8.94	8.63	5.96	3.61	2.04	1.10
3.61	6.59	8.94	8.94	8.94	5.96	3.61	1.88	1.10
3.29	6.12	8.63	8.94	8.15	5.49	3.61	1.88	1.10
2.67	4.39	6.27	6.74	5.96	4.08	2.67	1.57	0.94
1.73	2.67	3.61	4.55	3.61	2.67	1.88	1.25	0.78

TG-1 @ 90 psi and 50 Diffuser and Mesh on Simulator Intensity [in./h]								
0.48	0.71	0.71	0.95	0.95	0.71	0.71	0.48	0.24
0.95	1.19	1.43	1.90	1.66	1.19	0.71	0.71	0.48
1.19	1.90	2.62	3.33	3.57	2.14	1.43	0.95	0.48
1.66	3.57	5.71	7.13	9.27	4.76	2.38	1.19	0.71
1.90	3.80	10.70	8.92	7.85	11.65	3.09	1.43	0.71
1.90	4.28	8.32	12.60	7.61	6.66	2.62	1.19	0.71
1.43	2.62	4.28	7.61	5.71	4.04	2.14	0.95	0.71
0.95	1.43	1.90	2.38	2.14	1.43	0.95	0.71	0.48
0.48	0.95	0.95	1.19	0.95	0.95	0.71	0.48	0.24

TG-1 @ 15 psi and 100 Diffuser Intensity [in./h]								
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.09	0.09	0.37	0.37	0.37	0.09	0.09	0.09
0.09	0.37	0.55	0.92	1.29	0.92	0.55	0.37	0.09
0.18	0.55	1.29	3.13	5.53	2.95	1.47	0.55	0.18
0.37	0.74	3.13	8.29	10.13	5.34	2.21	0.74	0.18
0.37	1.29	3.87	10.13	10.50	7.00	2.03	1.29	0.18
0.37	1.11	2.76	7.19	9.58	5.34	1.47	0.37	0.09
0.37	0.92	1.66	2.95	2.95	1.84	0.74	0.37	0.09
0.18	0.37	0.55	0.74	0.74	0.55	0.37	0.18	0.09

TG-1 @ 40 psi and 100 Diffuser Intensity [in./h]								
1.11	1.47	1.84	2.21	2.03	1.47	0.92	0.55	0.37
1.47	2.21	3.13	3.69	3.13	2.40	1.29	0.74	0.37
2.40	3.69	5.34	5.71	3.32	3.69	2.03	1.11	0.55
3.50	5.34	8.48	9.21	7.19	4.79	2.76	1.29	0.74
4.24	7.37	9.77	9.77	8.11	5.16	2.76	1.47	0.55
3.69	6.82	9.21	9.77	7.55	4.79	2.58	1.29	0.55
3.13	5.16	7.37	7.55	5.90	3.87	2.40	1.11	0.55
2.21	3.50	4.24	4.79	3.69	2.40	1.47	0.92	0.55
1.66	2.03	2.40	2.76	1.47	1.66	1.11	0.74	0.55

TG-1 @ 90 psi and 100 Diffuser Intensity [in./h]								
4.29	5.66	7.37	7.54	6.17	4.80	3.60	2.57	1.37
4.97	6.68	7.88	8.40	6.86	5.14	3.60	2.57	1.71
5.49	7.54	9.26	8.74	7.20	5.31	3.77	2.74	1.89
6.00	8.91	9.77	9.77	7.20	5.14	3.60	2.91	2.06
6.09	9.77	9.77	9.77	7.37	4.97	3.77	2.91	2.06
6.17	9.26	9.77	9.77	7.71	5.14	3.77	2.91	2.23
5.66	8.06	9.77	9.77	7.37	5.14	3.94	3.09	2.23
4.46	6.86	8.57	9.77	7.03	5.31	4.11	2.91	2.23
3.60	4.97	6.17	6.68	6.17	3.43	2.23	2.91	2.23

SS4.3W @ 40 psi and 100 Diffuser Intensity [in./h]								
2.21	2.03	2.03	1.84	2.03	2.03	2.03	2.21	2.21
2.03	1.84	1.84	1.84	1.84	1.84	2.03	1.66	2.21
2.03	1.84	1.66	1.66	1.84	1.84	1.84	2.03	2.03
2.03	1.84	1.66	1.66	1.66	1.84	1.84	2.03	2.03
1.84	1.66	1.66	1.66	1.66	1.84	1.84	2.03	2.03
1.84	1.66	1.66	1.84	1.66	1.66	1.66	1.84	2.03
1.84	1.84	1.84	1.84	1.66	1.66	1.84	1.84	2.03
2.03	1.84	1.84	1.84	1.84	1.84	1.84	1.84	2.03
2.03	1.84	1.84	1.84	1.84	1.84	2.03	2.03	2.03

SS4.3W @ 90 psi and 100 Diffuser Intensity [in./h]								
3.95	4.13	3.95	5.39	6.29	6.83	6.83	6.83	6.29
3.60	3.60	3.95	4.67	5.21	5.75	5.93	6.11	5.93
3.42	3.24	3.42	3.95	4.67	5.03	5.57	5.57	5.39
3.06	2.88	3.24	3.78	3.95	4.49	4.85	5.03	5.03
3.06	2.88	3.24	3.24	3.60	3.95	4.31	4.67	4.85
3.06	2.88	3.06	3.42	3.42	3.78	3.95	4.13	4.49
3.06	2.88	3.06	3.24	3.42	3.42	3.78	4.13	4.49
3.06	3.06	3.24	3.24	3.42	3.42	3.78	3.95	4.31
3.06	3.06	3.06	3.42	3.42	3.60	3.95	3.95	4.31

FL5-VS @ 90 psi and 100 Diffuser Intensity [in./h]								
1.07	1.23	1.23	1.23	1.23	1.23	1.23	1.38	1.38
1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.38	1.38
1.23	1.07	1.07	1.07	1.23	1.23	1.23	1.23	1.23
1.23	1.07	1.23	1.23	1.23	1.23	1.23	1.23	1.38
1.07	1.23	1.23	1.07	1.07	1.23	1.23	1.38	1.38
1.23	1.23	1.07	1.07	1.07	1.23	1.23	1.23	1.38
1.23	1.23	1.23	1.07	1.23	1.23	1.23	1.38	1.38
1.23	1.38	1.38	1.07	1.23	1.23	1.23	1.38	1.38
1.23	1.38	1.23	1.38	1.38	1.38	1.38	1.38	1.38

Appendix B. Spore Washoff Procedure-Rain

Preparation

Sterilize the following materials in the airlock (4 hours, 200 ppm vaporous hydrogen peroxide):

- Aerosol dose apparatuses (ADAs) (6)
- Collection bin with coupon holder (1)
- Mesh droplet dispersion screen (1)

Sterilize the following materials in the autoclave (250°C gravity cycle):

- Stainless steel coupons (4)
- Concrete coupons (3, used coupons re-sterilized in autoclave)

Sterilize the deionized water tank as follows:

- Pour 50 mL of germicidal bleach into the tank and fill the tank with deionized water. (Let sit for at least one hour.)
- Run the tank water through the pump bypass; empty the tank into the sink
- Fill and empty the tank two times with deionized water; run rinse water through hose to outside storm drain
- Fill the tank with deionized water. Test that the free available chlorine is non-detectable at outlet end. Take a 50-mL sample from both the tank and from the nozzle head to test sterility.

Day 1

- Set up tables with bench liner. Remove a metered dose inhaler (E7) from refrigerator.
- Assemble concrete coupons on table with ADAs.
- Assemble three stainless steel coupons on table with ADAs.
- Perform sterility swabs on a concrete coupon, a stainless-steel coupon, an ADA, mesh, and manifold
- Label the coupons with sample ID per QAPP

Day 2

- Center the nozzle apparatus and set to achieve desired rainfall intensity. Take several flow checks using a collection bin to verify the desired rate is being achieved, and adjust settings if necessary.
- Aseptically place the first concrete coupon into the sterilized bin/coupon holder. Ensure the coupon is centered underneath the apparatus.
- Turn rainmaker on and collect the first 5 seconds of runoff in a falcon tube. After this initial collection periodically collect a 5-second sample after 6, 10, 18, 32, and 60 minutes.
- Stop the rainmaker and open the outlet valve.
- Remove the concrete coupon from the coupon holder and set aside. Wipe down the collection bin with dispatch wipes, sodium thiosulfate wipes, and ethyl alcohol. Run sterile water through the bin and collection valve; take a free available chlorine measurement of a rinse sample to verify non-detect for chlorine. Take a sterility swab sample of the interior of the bin.
- Wipe sample the inoculation control coupons.
- Deliver samples to onsite microbiology laboratory with chain of custody for analysis.

Appendix C. 10-ft. Rainfall Spore Washoff Results

These data were generated using the nozzles outlined in the "description" column of the table. The colony forming unit (CFU) values were obtained using the NHSRC onsite microbiology lab at EPA's research facility in Research Triangle Park (RTP)'s miscellaneous operating procedure (MOP) 6608 for spiral plating, incubating, and enumerating target organisms. The CFU values reported in this Appendix represent the number of spores collected in the runoff water sample at the notated timestamp.

Description	Sample ID	CFU	Timestamp (s from start)	Log CFU
Rain Test with mesh (2 M1 nozzles) *Bg* spores-dry deposition 0.5 in/h Replicate 1	59-AR0.5-D1-C-L-1a	2.94E+04	0	4.47
	59-AR0.5-D1-C-L-1a	4.03E+04	5	4.61
	59-AR0.5-D1-C-L-1a	2.51E+04	18	4.40
	59-AR0.5-D1-C-L-1a	4.33E+04	40	4.64
	59-AR0.5-D1-C-L-1a	2.98E+04	88	4.47
	59-AR0.5-D1-C-L-1a	3.43E+04	188	4.54
	59-AR0.5-D1-C-L-1a	1.32E+04	397	4.12
	59-AR0.5-D1-C-L-1a	1.04E+04	829	4.01
	59-AR0.5-D1-C-L-1a	8.00E+03	1727	3.90
	59-AR0.5-D1-C-L-1a	3.05E+03	3592	3.48
Rain Test with mesh (2 M1 nozzles) *Bg* spores-dry deposition 0.5 in/h Inoculation Control	AR0.5/AR6-D1-SS-W-1	2.02E+07	NA	7.31
	AR0.5/AR6-D1-SS-W-2	3.70E+07	NA	7.57
	AR0.5/AR6-D1-SS-W-3	2.80E+07	NA	7.45
Rain Test with mesh (2 M1 nozzles) *Bg* spores-dry deposition 0.5 in/h Replicate 2	59-AR0.5-D2-C-L-1a	1.57E+05	0	5.20
	59-AR0.5-D2-C-L-1b	6.30E+04	5	4.80
	59-AR0.5-D2-C-L-1c	3.78E+04	17	4.58
	59-AR0.5-D2-C-L-1d	7.73E+04	40	4.89
	59-AR0.5-D2-C-L-1e	2.29E+04	88	4.36
	59-AR0.5-D2-C-L-1f	1.52E+04	188	4.18
	59-AR0.5-D2-C-L-1g	3.12E+04	397	4.49
	59-AR0.5-D2-C-L-1h	6.95E+03	829	3.84
	59-AR0.5-D2-C-L-1i	2.55E+03	1727	3.41
	59-AR0.5-D2-C-L-1j	4.21E+03	3592	3.62
Rain Test with mesh (2 M1 nozzles) *Bg* spores-dry deposition 0.5 in/h Inoculation Control	59-AR0.5/AR6-D2-SS-W-1	4.96E+07	inoculation control	7.70
	59-AR0.5/AR6-D2-SS-W-2	3.84E+07	inoculation control	7.58
	59-AR0.5/AR6-D2-SS-W-3	4.34E+07	inoculation control	7.64

Description	Sample ID	CFU	Timestamp (s from start)	Log CFU
Rain Test with mesh (1 M3 nozzle) *Bg* spores-dry deposition 1 in/h Replicate 1	59-AR1-D1-C-L-1a	4.79E+04	0	4.68
	59-AR1-D1-C-L-1b	1.88E+04	5	4.27
	59-AR1-D1-C-L-1c	1.43E+04	17	4.15
	59-AR1-D1-C-L-1d	5.16E+03	91	3.71
	59-AR1-D1-C-L-1e	9.54E+03	113	3.98
	59-AR1-D1-C-L-1f	6.30E+03	230	3.80
	59-AR1-D1-C-L-1g	1.11E+04	397	4.05
	59-AR1-D1-C-L-1h	1.79E+04	829	4.25
	59-AR1-D1-C-L-1i	1.65E+04	1727	4.22
	59-AR1-D1-C-L-1j	4.24E+03	3592	3.63
Rain Test with mesh (1 M3 nozzle) *Bg* spores-dry deposition 1 in/h Inoculation Control	59-AR1-D1/D2-SS-W-1	2.98E+07	NA	7.47
	59-AR1-D1/D2-SS-W-2	5.42E+07	NA	7.73
	59-AR1-D1/D2-SS-W-3	4.86E+07	NA	7.69
Rain Test with mesh (1 M3 nozzle) *Bg* spores-dry deposition 1 in/h Replicate 2	59-AR1-D2-C-L-1a	1.99E+04	0	4.30
	59-AR1-D2-C-L-1b	8.40E+03	5	3.92
	59-AR1-D2-C-L-1c	2.58E+03	17	3.41
	59-AR1-D2-C-L-1d	9.47E+03	40	3.98
	59-AR1-D2-C-L-1e	1.14E+04	83	4.06
	59-AR1-D2-C-L-1f	5.48E+03	188	3.74
	59-AR1-D2-C-L-1g	2.53E+04	397	4.40
	59-AR1-D2-C-L-1h	2.35E+04	829	4.37
	59-AR1-D2-C-L-1i	6.80E+03	1727	3.83
	59-AR1-D2-C-L-1j	3.60E+03	3592	3.56
Rain Test with mesh (1 M3 nozzle) *Bg* spores-dry deposition 1 in/h Inoculation Control	59-AR1-D1/D2-SS-W-1	2.98E+07	NA	7.47
	59-AR1-D1/D2-SS-W-2	5.42E+07	NA	7.73
	59-AR1-D1/D2-SS-W-3	4.86E+07	NA	7.69

Description	Sample ID	CFU	Timestamp (s from start)	Log CFU
Rain Test with mesh (M1 + M3 + M5) *Bg* spores-dry deposition 3 in/h Replicate 1	59-AR3-D2-C-L-1a	4.37E+05	0	5.64
	59-AR3-D2-C-L-1b	3.73E+04	5	4.57
	59-AR3-D2-C-L-1c	3.17E+04	17	4.50
	59-AR3-D2-C-L-1d	4.11E+04	40	4.61
	59-AR3-D2-C-L-1e	6.91E+04	88	4.84
	59-AR3-D2-C-L-1f	4.24E+04	188	4.63
	59-AR3-D2-C-L-1g	2.00E+04	397	4.30
	59-AR3-D2-C-L-1h	4.03E+03	829	3.61
	59-AR3-D2-C-L-1i	7.82E+03	1729	3.89
	59-AR3-D2-C-L-1j	2.54E+03	3592	3.41
Rain Test with mesh (M1 + M3 + M5) *Bg* spores-dry deposition 3 in/h Inoculation Control	59-AR3-D2/D3-SS-W-1	4.78E+07	NA	7.68
	59-AR3-D2/D3-SS-W-2	3.76E+07	NA	7.58
	59-AR3-D2/D3-SS-W-3	4.50E+07	NA	7.65
Rain Test with mesh (M1 + M3 + M5) *Bg* spores-dry deposition 3 in/h Replicate 2	59-AR3-D3-C-L-1a	9.20E+04	0	4.96
	59-AR3-D3-C-L-1b	1.45E+05	6	5.16
	59-AR3-D3-C-L-1c	1.33E+05	17	5.12
	59-AR3-D3-C-L-1d	7.26E+04	45	4.86
	59-AR3-D3-C-L-1e	6.09E+04	88	4.78
	59-AR3-D3-C-L-1f	4.13E+04	188	4.62
	59-AR3-D3-C-L-1g	2.14E+04	397	4.33
	59-AR3-D3-C-L-1h	2.96E+04	829	4.47
	59-AR3-D3-C-L-1i	6.93E+03	1727	3.84
	59-AR3-D3-C-L-1j	1.84E+03	3592	3.26
Rain Test with mesh (M1 + M3 + M5) *Bg* spores-dry deposition 3 in/h Inoculation Control	59-AR3-D2/D3-SS-W-1	4.78E+07	NA	7.68
	59-AR3-D2/D3-SS-W-2	3.76E+07	NA	7.58
	59-AR3-D2/D3-SS-W-3	4.50E+07	NA	7.65

Description	Sample ID	CFU	Timestamp (s from start)	Log CFU
Rain Test with mesh (2 M15 + 1 M5) *Bg* spores-dry deposition 6 in/h Replicate 1	59-AR6-D1-C-L-1a	2.78E+04	0	4.44
	59-AR6-D1-C-L-1b	4.12E+04	5	4.61
	59-AR6-D1-C-L-1c	2.62E+04	17	4.42
	59-AR6-D1-C-L-1d	2.30E+04	40	4.36
	59-AR6-D1-C-L-1e	1.21E+05	88	5.08
	59-AR6-D1-C-L-1f	6.10E+04	188	4.79
	59-AR6-D1-C-L-1g	1.94E+04	397	4.29
	59-AR6-D1-C-L-1h	1.52E+04	829	4.18
	59-AR6-D1-C-L-1i	6.64E+03	1727	3.82
	59-AR6-D1-C-L-1j	8.31E+03	3592	3.92
Rain Test with mesh (2 M15 + 1 M5) *Bg* spores-dry deposition 6 in/h Inoculation Control	AR0.5/AR6-D1-SS-W-1	2.02E+07	NA	7.31
	AR0.5/AR6-D1-SS-W-2	3.70E+07	NA	7.57
	AR0.5/AR6-D1-SS-W-3	2.80E+07	NA	7.45
Rain Test with mesh (2 M15 + 1 M5) *Bg* spores-dry deposition 6 in/h Replicate 1	59-AR6-D2-C-L-1a	9.02E+04	0	4.96
	59-AR6-D2-C-L-1b	1.47E+05	5	5.17
	59-AR6-D2-C-L-1c	2.42E+05	17	5.38
	59-AR6-D2-C-L-1d	1.16E+05	61	5.07
	59-AR6-D2-C-L-1e	1.18E+05	88	5.07
	59-AR6-D2-C-L-1f	4.22E+04	188	4.63
	59-AR6-D2-C-L-1g	1.74E+04	397	4.24
	59-AR6-D2-C-L-1h	1.66E+04	829	4.22
	59-AR6-D2-C-L-1i	1.08E+04	1727	4.03
	59-AR6-D2-C-L-1j	2.67E+03	3592	3.43
Rain Test with mesh (2 M15 + 1 M5) *Bg* spores-dry deposition 6 in/h Inoculation Control	59-AR0.5/AR6-D2-SS-W-1	4.96E+07	NA	7.70
	59-AR0.5/AR6-D2-SS-W-2	3.84E+07	NA	7.58
	59-AR0.5/AR6-D2-SS-W-3	4.34E+07	NA	7.64

Description	Sample ID	CFU	Timestamp (s from start)	Log CFU
Rain Test no mesh (2 M1 nozzles) *Bg* spores-dry deposition 0.5 in/h Replicate 1	59-AR0.5N-D1-C-L-1a	8.31E+03	0	3.92
	59-AR0.5N-D1-C-L-1b	1.56E+04	5	4.19
	59-AR0.5N-D1-C-L-1c	2.52E+04	17	4.40
	59-AR0.5N-D1-C-L-1d	3.60E+03	40	3.56
	59-AR0.5N-D1-C-L-1e	6.35E+03	88	3.80
	59-AR0.5N-D1-C-L-1f	9.42E+03	188	3.97
	59-AR0.5N-D1-C-L-1g	6.47E+03	397	3.81
	59-AR0.5N-D1-C-L-1h	2.88E+03	829	3.46
	59-AR0.5N-D1-C-L-1i	3.09E+03	1727	3.49
	59-AR0.5N-D1-C-L-1j	2.79E+03	3592	3.45
Rain Test no mesh (2 M1 nozzles) *Bg* spores-dry deposition 0.5 in/h Inoculation Control	59-AR0.5N-D1/D2-SS-W-1	3.24E+07	NA	7.51
	59-AR0.5N-D1/D2-SS-W-2	4.42E+07	NA	7.65
	59-AR0.5N-D1/D2-SS-W-3	3.26E+07	NA	7.51
Rain Test no mesh (2 M1 nozzles) *Bg* spores-dry deposition 0.5 in/h Replicate 2	59-AR0.5N-D2-C-L-1a	4.13E+04	0	4.62
	59-AR0.5N-D2-C-L-1b	4.20E+04	5	4.62
	59-AR0.5N-D2-C-L-1c	1.94E+04	17	4.29
	59-AR0.5N-D2-C-L-1d	3.40E+03	40	3.53
	59-AR0.5N-D2-C-L-1e	3.15E+03	88	3.50
	59-AR0.5N-D2-C-L-1f	3.12E+03	188	3.49
	59-AR0.5N-D2-C-L-1g	1.24E+04	397	4.09
	59-AR0.5N-D2-C-L-1h	9.59E+02	829	2.98
	59-AR0.5N-D2-C-L-1i	3.75E+03	1727	3.57
	59-AR0.5N-D2-C-L-1j	5.83E+02	3592	2.77
Rain Test no mesh (2 M1 nozzles) *Bg* spores-dry deposition 0.5 in/h Inoculation Control	59-AR0.5N-D1/D2-SS-W-1	3.24E+07	NA	7.51
	59-AR0.5N-D1/D2-SS-W-2	4.42E+07	NA	7.65
	59-AR0.5N-D1/D2-SS-W-3	3.26E+07	NA	7.51

Description	Sample ID	CFU	Timestamp (s from start)	Log CFU
Rain Test no mesh (1 M3 nozzle) *Bg* spores-dry deposition 1 in/h Replicate 1	59-AR1N-D1-C-L-1a	1.73E+05	0	5.24
	59-AR1N-D1-C-L-1b	4.58E+04	5	4.66
	59-AR1N-D1-C-L-1c	1.74E+04	35	4.24
	59-AR1N-D1-C-L-1d	1.11E+04	60	4.05
	59-AR1N-D1-C-L-1e	1.39E+04	210	4.14
	59-AR1N-D1-C-L-1f	5.04E+03	219	3.70
	59-AR1N-D1-C-L-1g	1.40E+04	397	4.15
	59-AR1N-D1-C-L-1h	3.25E+03	829	3.51
	59-AR1N-D1-C-L-1i	3.38E+03	1727	3.53
	59-AR1N-D1-C-L-1j	1.44E+03	3592	3.16
Rain Test no mesh (1 M3 nozzle) *Bg* spores-dry deposition 1 in/h Inoculation Control	59-AR1N-D1/D2-SS-W-1	6.18E+07	NA	7.79
	59-AR1N-D1/D2-SS-W-2	1.09E+08	NA	8.04
	59-AR1N-D1/D2-SS-W-3	9.66E+07	NA	7.98
Rain Test no mesh (1 M3 nozzle) *Bg* spores-dry deposition 1 in/h Replicate 2	59-AR1N-D2-C-L-1a	7.58E+04	0	4.88
	59-AR1N-D2-C-L-1b	3.44E+04	5	4.54
	59-AR1N-D2-C-L-1c	3.67E+04	17	4.56
	59-AR1N-D2-C-L-1d	2.51E+04	42	4.40
	59-AR1N-D2-C-L-1e	7.05E+04	88	4.85
	59-AR1N-D2-C-L-1f	2.70E+04	188	4.43
	59-AR1N-D2-C-L-1g	1.07E+04	397	4.03
	59-AR1N-D2-C-L-1h	6.56E+03	829	3.82
	59-AR1N-D2-C-L-1i	2.72E+03	1727	3.44
	59-AR1N-D2-C-L-1j	3.00E+03	3592	3.48
Rain Test no mesh (1 M3 nozzle) *Bg* spores-dry deposition 1 in/h Inoculation Control	59-AR1N-D1/D2-SS-W-1	6.18E+07	NA	7.79
	59-AR1N-D1/D2-SS-W-2	1.09E+08	NA	8.04
	59-AR1N-D1/D2-SS-W-3	9.66E+07	NA	7.98
Rain Test no mesh (M1 + M3 + M5) *Bg* spores-dry deposition 3 in/h Replicate 1	59-AR3N-D1-C-L-1a	8.06E+03	0	3.91
	59-AR3N-D1-C-L-1b	4.91E+03	5	3.69
	59-AR3N-D1-C-L-1c	1.05E+04	17	4.02
	59-AR3N-D1-C-L-1d	8.66E+03	40	3.94
	59-AR3N-D1-C-L-1e	7.56E+03	88	3.88
	59-AR3N-D1-C-L-1f	4.62E+03	188	3.66
	59-AR3N-D1-C-L-1g	1.93E+03	397	3.28
	59-AR3N-D1-C-L-1h	6.91E+03	829	3.84
	59-AR3N-D1-C-L-1i	1.79E+03	1727	3.25
	59-AR3N-D1-C-L-1j	1.09E+03	3592	3.04

Description	Sample ID	CFU	Timestamp (s from start)	Log CFU
Rain Test no mesh (M1 + M3 + M5) *Bg* spores-dry deposition 3 in/h Inoculation Control	59-AR3N-D1/D2-SS-W-1	4.58E+07	NA	7.66
	59-AR3N-D1/D2-SS-W-2	3.66E+07	NA	7.56
	59-AR3N-D1/D2-SS-W-3	4.70E+07	NA	7.67
Rain Test no mesh (M1 + M3 + M5) *Bg* spores-dry deposition 3 in/h Replicate 2	59-AR3N-D2-C-L-1a	0	0	0
	59-AR3N-D2-C-L-1b	7.34E+03	5	3.87
	59-AR3N-D2-C-L-1c	7.03E+03	17	3.85
	59-AR3N-D2-C-L-1d	4.49E+03	40	3.65
	59-AR3N-D2-C-L-1e	2.06E+04	88	4.31
	59-AR3N-D2-C-L-1f	1.27E+04	188	4.10
	59-AR3N-D2-C-L-1g	4.14E+01	397	1.62
	59-AR3N-D2-C-L-1h	5.95E+03	829	3.77
	59-AR3N-D2-C-L-1i	2.43E+03	1727	3.38
	59-AR3N-D2-C-L-1j	7.20E+02	3592	2.86
Rain Test no mesh (M1 + M3 + M5) *Bg* spores-dry deposition 3 in/h Inoculation Control	59-AR3N-D1/D2-SS-W-1	4.58E+07	NA	7.66
	59-AR3N-D1/D2-SS-W-2	3.66E+07	NA	7.56
	59-AR3N-D1/D2-SS-W-3	4.70E+07	NA	7.67
Rain Test no mesh (2 M15 + 1 M5) *Bg* spores-dry deposition 6 in/h Replicate 1	59-AR6N-D1-C-L-1a	2.78E+03	0	3.44
	59-AR6N-D1-C-L-1b	1.07E+04	5	4.03
	59-AR6N-D1-C-L-1c	1.70E+04	17	4.23
	59-AR6N-D1-C-L-1d	1.87E+04	40	4.27
	59-AR6N-D1-C-L-1e	9.20E+03	88	3.96
	59-AR6N-D1-C-L-1f	7.26E+03	188	3.86
	59-AR6N-D1-C-L-1g	1.54E+04	397	4.19
	59-AR6N-D1-C-L-1h	1.15E+04	829	4.06
	59-AR6N-D1-C-L-1i	5.46E+03	1727	3.74
	59-AR6N-D1-C-L-1j	2.20E+03	3592	3.34
Rain Test with mesh (2 M15 + 1 M5) *Bg* spores-dry deposition 6 in/h Inoculation Control	59-AR6N-D1/D2-SS-W-1	2.68E+07	NA	7.43
	59-AR6N-D1/D2-SS-W-2	4.72E+07	NA	7.67
	59-AR6N-D1/D2-SS-W-3	5.66E+07	NA	7.75

Description	Sample ID	CFU	Timestamp (s from start)	Log CFU
Rain Test with mesh (2 M15 + 1 M5) *Bg* spores-dry deposition 6 in/h Replicate 2	59-AR6N-D2-C-L-1a	8.45E+04	0	4.93
	59-AR6N-D2-C-L-1b	2.86E+04	5	4.46
	59-AR6N-D2-C-L-1c	8.14E+04	17	4.91
	59-AR6N-D2-C-L-1d	1.01E+05	40	5.00
	59-AR6N-D2-C-L-1e	6.52E+04	88	4.81
	59-AR6N-D2-C-L-1f	7.35E+04	188	4.87
	59-AR6N-D2-C-L-1g	3.36E+04	397	4.53
	59-AR6N-D2-C-L-1h	1.14E+04	829	4.06
	59-AR6N-D2-C-L-1i	1.68E+03	1727	3.23
	59-AR6N-D2-C-L-1j	8.79E+02	3592	2.94
Rain Test with mesh (2 M15 + 1 M5) *Bg* spores-dry deposition 6 in/h Inoculation Control	59-AR6N-D1/D2-SS-W-1	2.68E+07	NA	7.43
	59-AR6N-D1/D2-SS-W-2	4.72E+07	NA	7.67
	59-AR6N-D1/D2-SS-W-3	5.66E+07	NA	7.75

Appendix D. 26-ft. Intensity Heat Maps

*Gray shaded headers are nozzle conditions selected for use in the spore washoff portion of this work. Refer to Section 3.1 in the body of the report for an explanation how these data were generated.

TG-1 (x1) @ 20 psi, 50 Diffuser Intensity [in./h]								
0.31	0.31	0.37	0.43	0.43	0.49	0.49	0.49	0.43
0.37	0.37	0.43	0.49	0.61	0.68	0.68	0.61	0.49
0.37	0.31	0.31	0.74	0.86	0.80	0.80	0.80	0.61
0.49	0.61	0.61	1.04	1.17	1.04	1.04	0.86	0.68
0.61	0.80	0.80	1.29	1.41	1.23	1.23	0.98	0.74
0.61	0.92	1.04	1.47	1.47	1.23	1.23	0.98	0.68
0.61	0.92	1.23	1.54	1.54	1.23	1.23	0.86	0.61
0.55	0.86	1.23	1.29	1.35	0.92	0.92	0.74	0.49
0.49	0.86	1.11	0.98	0.98	0.74	0.74	0.55	0.43
TG-1 (x2) @ 20 psi, 50 Diffuser, 1-hour duration Intensity [in./h]								
0.74	0.98	1.23	1.60	1.84	2.09	2.33	2.58	2.64
0.98	1.23	1.54	1.90	2.21	2.64	2.95	3.13	3.38
1.04	1.41	1.84	2.21	2.52	3.13	3.56	3.56	3.56
1.29	1.72	2.21	2.83	3.32	3.56	3.56	3.56	3.56
1.54	1.90	2.52	3.19	3.56	3.56	3.56	3.56	3.56
1.60	2.15	2.70	3.56	3.56	3.56	3.56	3.56	3.56
1.66	2.27	2.95	3.56	3.56	3.56	3.56	3.56	3.56
1.66	2.27	3.07	3.56	3.56	3.56	3.56	3.56	3.56
1.54	2.21	2.95	3.56	3.56	3.56	3.56	3.56	3.56
TG-1 (x2) @ 20 PSI, 50 Diffuser, 22 min duration Intensity [in./h]								
1.34	1.68	2.01	2.01	2.68	3.02	3.35	3.52	3.69
1.68	2.01	2.51	2.51	3.18	3.69	3.85	4.19	4.36
2.01	2.51	3.18	3.18	4.02	4.19	4.86	5.03	5.03
2.51	3.18	3.69	3.69	4.69	5.19	5.19	5.86	5.86
3.18	3.69	4.19	4.19	5.36	5.86	6.37	6.53	6.53
4.02	4.69	5.19	5.19	6.37	6.70	7.20	7.37	7.04
4.69	5.36	5.36	5.36	7.37	7.71	8.04	7.71	7.54
5.03	6.37	7.04	7.04	8.21	8.38	8.38	8.21	7.54
5.53	6.53	7.54	7.54	8.88	9.05	8.88	8.21	7.37

FL5-VS (x1), 40 psi, 50 Diffuser Intensity [in./h]								
2.03	2.03	2.03	1.84	2.03	2.03	2.03	2.03	2.03
2.03	2.03	2.03	1.84	2.03	2.03	1.84	1.84	2.03
2.03	2.03	2.03	1.84	2.03	1.84	1.84	1.84	1.84
2.03	2.03	2.03	1.84	1.84	1.84	1.84	1.84	1.84
2.03	2.03	1.84	1.84	1.84	1.84	1.84	1.84	1.84
2.03	2.03	1.84	1.84	1.84	1.84	1.84	1.84	1.84
2.03	2.03	1.84	1.84	1.84	1.84	1.84	1.84	1.84
2.03	2.03	1.84	1.84	1.84	1.84	1.84	1.84	1.84
2.03	2.03	1.84	1.84	1.84	1.84	1.84	1.84	1.84

FL5-VS (x1), 50 psi, 50 Diffuser Intensity [in./h]								
0.68	0.68	0.68	0.74	0.74	0.80	0.80	0.80	0.80
0.68	0.68	0.68	0.74	0.74	0.80	0.80	0.80	0.80
0.68	0.68	0.68	0.74	0.74	0.74	0.86	0.80	0.80
0.68	0.68	0.74	0.74	0.80	0.80	0.80	0.80	0.80
0.68	0.68	0.74	0.74	0.80	0.80	0.80	0.80	0.80
0.68	0.68	0.74	0.74	0.80	0.80	0.80	0.80	0.80
0.68	0.68	0.74	0.74	0.80	0.80	0.80	0.80	0.80
0.68	0.68	0.74	0.74	0.80	0.80	0.86	0.86	0.83
0.68	0.74	0.74	0.80	0.86	0.86	0.86	0.86	0.83

FL5-VS (x2), 50 psi, 50 Diffuser Intensity [in./h]								
1.60	1.60	1.54	1.60	1.54	1.54	1.60	1.66	1.72
1.72	1.66	1.66	1.60	1.60	1.66	1.60	1.66	1.78
1.72	1.72	1.72	1.72	1.66	1.60	1.72	1.66	1.78
1.78	1.78	1.78	1.72	1.72	1.72	1.72	1.72	1.78
1.84	1.78	1.78	1.84	1.78	1.78	1.84	1.72	1.84
1.90	1.90	1.84	1.84	1.84	1.84	1.84	1.84	1.90
2.03	1.97	1.90	1.90	1.97	1.90	1.97	1.97	2.03
2.21	2.03	2.09	2.03	2.03	2.03	2.03	2.03	2.15
2.21	2.64	2.15	2.21	2.15	2.15	2.15	2.15	2.15

HH-1, 5 psi, iteration 1 Intensity [in./h]								
4.61	5.34	5.90	6.27	6.45	6.63	6.45	6.45	6.08
4.42	5.16	5.71	5.90	6.27	6.27	6.27	5.90	5.71
4.24	4.79	5.16	5.53	5.53	5.53	5.53	5.34	4.98
3.69	4.24	4.61	4.79	4.79	4.79	4.61	4.61	4.24
3.50	3.69	3.87	4.05	4.05	4.05	3.87	3.69	3.69
2.95	3.32	3.50	3.50	3.50	3.32	3.13	3.32	2.95
2.76	2.95	2.95	2.95	2.95	2.76	2.76	2.58	2.40
2.21	2.40	2.40	2.40	2.40	2.21	2.21	2.21	1.84
2.03	2.03	2.03	2.03	1.84	1.84	1.84	1.84	1.84

HH-1, 5 psi, iteration 2 Intensity [in./h]								
0.55	0.55	0.55	0.55	0.74	0.55	0.55	0.55	0.55
0.55	0.74	0.74	0.74	0.92	0.92	0.92	0.74	0.92
0.74	0.92	0.92	1.11	1.29	1.29	1.11	1.66	1.11
0.74	1.11	1.29	1.47	1.66	1.66	1.66	1.84	1.47
0.92	1.29	1.47	1.84	1.84	2.03	2.03	2.21	1.84
0.92	1.29	1.66	2.03	2.21	2.21	2.58	2.58	2.03
1.11	1.47	1.84	2.21	2.40	2.58	2.58	2.76	2.40
1.11	1.66	1.84	2.40	2.58	2.76	2.76	2.76	2.40
0.92	1.47	1.84	2.40	2.58	2.76	2.95	2.95	2.58

HH-1, 5 psi, iteration 3 Intensity [in./h]								
0.55	0.55	0.74	0.92	0.92	0.92	1.11	1.11	1.11
0.55	0.74	0.92	1.11	1.11	1.47	1.47	1.47	1.29
0.74	0.92	1.11	1.29	1.29	1.47	1.66	1.66	1.29
0.74	0.92	1.29	1.66	1.66	1.84	2.03	1.84	1.47
0.74	1.11	1.47	1.84	1.84	2.21	2.21	1.84	1.47
0.74	1.11	1.47	2.03	2.03	2.21	2.21	1.84	1.47
0.74	1.11	1.47	2.03	2.03	2.21	2.40	1.84	1.47
0.74	0.92	1.29	1.84	1.84	2.21	2.21	1.84	1.29
0.55	0.92	1.11	1.47	1.47	1.66	1.84	1.47	1.29

HH-1, 5 psi, iteration 4 Intensity [in./h]								
0.18	0.37	0.37	0.37	0.55	0.55	0.55	0.74	0.74
0.18	0.37	0.37	0.55	0.55	0.55	0.74	0.74	0.92
0.37	0.55	0.55	0.55	0.55	0.74	0.92	0.92	1.11
0.55	0.55	0.55	0.74	0.74	1.11	1.11	1.29	1.29
0.55	0.74	0.74	0.92	1.11	1.29	1.29	1.47	1.29
0.55	0.92	1.11	1.29	1.29	1.66	1.84	1.66	1.47
0.55	0.92	1.29	1.47	1.84	1.84	2.03	1.84	1.47
0.74	0.92	1.29	1.66	2.03	2.03	2.21	2.03	1.47
0.74	0.92	1.29	1.66	2.21	2.40	2.58	2.03	1.66

HH-1, 20 psi Intensity [in./h]								
1.29	1.47	1.66	2.03	2.21	2.76	2.76	2.95	2.58
1.66	1.84	2.03	2.40	2.76	3.13	3.50	3.50	3.32
2.03	2.21	2.40	2.76	3.32	3.69	4.05	4.05	3.87
2.40	2.58	2.76	3.32	3.69	4.05	4.42	4.61	4.42
2.58	2.95	3.13	3.50	4.05	4.42	4.61	4.98	4.61
2.95	2.95	3.32	3.69	4.05	4.42	4.79	4.79	4.61
2.95	3.13	3.32	3.69	4.05	4.24	4.42	4.42	4.24
2.58	2.76	2.95	3.32	3.69	3.69	3.87	3.87	3.50
2.21	2.40	2.58	2.76	2.95	3.13	3.13	2.95	2.95

HH-1 (x2), 5 psi Intensity [in./h]								
1.11	1.29	1.66	1.84	2.03	1.84	1.47	1.11	0.92
1.47	1.84	2.03	2.21	2.21	2.03	1.66	1.29	0.92
2.03	2.03	2.40	2.40	2.40	2.03	1.84	1.29	0.92
2.40	2.76	2.95	2.95	2.58	2.40	1.84	1.29	0.92
3.32	3.32	3.32	3.13	2.95	2.40	1.84	1.29	0.92
3.69	3.87	3.69	3.32	2.95	2.40	1.84	1.29	0.92
3.87	4.05	3.87	3.50	3.13	2.40	2.03	1.29	1.11
3.69	3.87	3.69	3.50	3.13	2.58	2.03	1.47	0.92
3.13	3.32	3.50	3.50	2.95	2.40	1.84	1.29	1.11

HH-6SQ, 5 psi, 1-hour duration Intensity [in./h]								
2.83	3.13	3.38	3.50	3.50	3.50	3.50	3.50	3.50
3.07	3.38	3.50	3.50	3.50	3.50	3.50	3.50	3.50
3.07	3.44	3.50	3.50	3.50	3.50	3.50	3.50	3.50
2.89	3.38	3.50	3.50	3.50	3.50	3.50	3.50	3.50
2.89	3.26	3.50	3.50	3.50	3.50	3.50	3.50	3.50
2.70	3.07	3.38	3.50	3.50	3.50	3.50	3.50	3.50
2.52	2.83	3.19	3.50	3.50	3.50	3.50	3.50	3.50
2.21	2.52	2.83	3.07	3.50	3.50	3.50	3.50	3.50
2.03	2.21	2.52	2.83	3.07	3.50	3.50	3.50	3.50

HH-6SQ, 5 psi, 20-minute duration Intensity [in./h]								
3.50	3.69	3.87	3.87	4.05	3.87	3.87	4.05	3.87
3.69	4.05	4.24	4.24	4.24	4.42	4.61	4.42	4.42
3.87	4.24	4.42	4.61	4.61	4.61	4.79	4.98	4.79
3.87	4.24	4.61	4.79	5.16	5.16	5.34	5.53	5.53
3.87	4.24	4.61	4.98	5.16	5.34	5.71	5.90	6.08
3.69	4.05	4.42	4.79	5.16	5.53	5.90	6.27	6.45
3.50	3.87	4.24	4.61	5.16	5.53	5.90	6.27	6.63
2.95	3.32	3.87	4.24	4.61	5.16	5.71	6.08	6.45
2.76	3.13	3.50	3.69	4.24	4.61	5.16	5.53	6.08

HH-14WSQ, 5 psi Intensity [in./h]								
0.74	0.74	0.92	0.92	0.92	0.74	0.74	0.74	0.74
0.74	0.92	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74
0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74

HH-30WSQ, 5 psi Intensity [in./h]								
2.03	2.21	2.21	2.40	2.40	2.58	2.76	2.58	2.76
2.03	2.21	2.21	2.40	2.40	2.58	2.76	2.76	2.76
2.21	2.21	2.21	2.40	2.58	2.58	2.58	2.58	2.76
2.03	2.21	2.21	2.40	2.58	2.58	2.58	2.76	2.76
2.21	2.40	2.40	2.40	2.58	2.40	2.76	2.76	2.76
2.21	2.40	2.40	2.40	2.58	2.58	2.58	2.76	2.76
2.21	2.40	2.40	2.40	2.58	2.58	2.76	2.76	2.76
2.21	2.40	2.40	2.40	2.58	2.58	2.58	2.76	2.76
2.40	2.40	2.40	2.40	2.76	2.76	2.76	2.76	3.13

HH-50WSQ, 5 psi Intensity [in./h]								
4.61	4.61	4.98	4.05	4.05	4.24	4.05	3.87	4.05
4.79	4.05	4.24	4.79	4.79	4.05	4.24	4.61	4.42
3.69	4.61	4.42	4.24	4.24	4.24	3.69	4.24	4.24
4.79	4.79	4.61	4.61	4.61	4.42	4.61	4.61	4.24
4.79	4.05	4.42	4.98	4.98	4.61	4.24	4.79	4.24
4.42	4.61	4.61	4.24	4.24	4.24	4.98	3.87	4.61
4.61	4.98	4.42	4.79	4.79	4.61	4.61	4.05	4.05
4.98	4.79	4.24	4.61	4.61	4.79	4.61	4.42	4.61
4.79	4.79	4.98	4.42	4.42	4.61	4.42	4.79	4.24

GG-1.5W, 5 psi Intensity [in./h]								
0.55	0.55	0.74	0.74	0.74	0.74	0.92	0.74	0.74
0.55	0.74	0.92	0.92	1.11	1.11	1.11	1.11	0.92
0.74	0.92	1.11	1.29	1.47	1.47	1.47	1.29	1.29
0.92	1.11	1.47	1.66	1.84	1.84	1.84	1.84	1.66
1.11	1.29	1.84	2.03	2.21	2.40	2.40	2.21	2.03
1.29	1.66	2.21	2.40	2.76	2.76	2.76	2.58	2.40
1.47	1.84	2.40	2.76	3.13	3.13	3.13	2.95	2.76
1.47	2.03	2.58	2.95	3.32	3.32	3.50	3.32	2.95
1.47	2.03	2.58	2.95	3.32	3.50	3.50	3.32	3.13

GG-2.8W, 5 psi Intensity [in./h]								
0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92

Appendix E. 26-ft. Rainfall Spore Washoff Results

These data were generated using the conditions specified in the top portion of the table. The colony forming unit (CFU) values reported for each test coupon were obtained using the NHSRC onsite microbiology lab at EPA's research facility in Research Triangle Park (RTP)'s miscellaneous operating procedure (MOP) 6608 for spiral plating, incubating, and enumerating target organisms. The CFU values reported in this Appendix represent the number of spores collected in the runoff water sample at the notated timestamp.

0.6 in./h		
Deposition	Dry	
Test ID	59-AR0.6	
Material Type	Concrete	
Spore Type	*Bg*	
Nozzle Part Number	HH-14WSQ	
Droplet Volume Mean Diameter	0.627	mm
Kinetic Energy	727	J/(m^{2}·h)
Number of Nozzles Used during Test	1	
Sample Collection Time	5	s
Intensity (20 min bin measurement)	0.64	in/h
Intensity (heat map)	0.56	in/h
Intensity (Parsivel2)	0.41	in/h
Positive Control	2.17E+07	CFU
Positive Control Stdev	5.99E+06	CFU

	Coupon 1			Coupon 2			Coupon 3		
Time Stamp (s)	Average Liquid CFU	Analyzed Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)
5	5.06E+03	22.20	2.20	4.77E+03	22.10	2.10	5.78E+03	23.10	3.10
10	2.43E+03	21.90	1.90	4.62E+03	22.00	2.00	6.04E+03	22.80	2.80
25	5.18E+02	20.70	0.70	2.82E+03	21.70	1.70	2.05E+02	20.50	0.50
35	5.49E+02	21.10	1.10	1.70E+03	21.30	1.30	1.68E+03	21.50	1.50
95	2.14E+03	22.30	2.30	5.61E+02	20.40	0.40	1.91E+03	22.00	2.00
185	3.21E+03	22.00	2.00	7.79E+02	20.50	0.50	1.77E+03	21.60	1.60
455	1.89E+03	22.80	2.80	6.27E+02	20.90	0.90	6.06E+02	20.90	0.90
845	3.00E+02	21.40	1.40	1.03E+03	21.00	1.00	1.29E+03	21.90	1.90
1805	5.86E+02	21.70	1.70	1.29E+02	21.50	1.50	7.37E+02	24.30	4.30
3600	3.28E+02	22.80	2.80	1.10E+02	21.20	1.20	6.99E+02	22.30	2.30

1 in./h		
Deposition	Dry	
Test ID	59-AR0.6	
Material Type	Concrete	
Spore Type	*Bg*	
Nozzle Part Number	GG-2.8W	
Droplet Volume Mean Diameter	0.60	mm
Kinetic Energy	46	$J/(m^{2}\cdot h)$
Number of Nozzles Used during Test	1	
Sample Collection Time	5	s
Intensity (20 min bin measurement)	0.98	in/h
Intensity (heat map)	0.92	in/h
Intensity (Parsivel2)	0.54	in/h
Positive Control	2.63E+07	CFU
Positive Control Stdev	4.13E+06	CFU

	Coupon 1			Coupon 2			Coupon 3		
Time Stamp (s)	Average Liquid CFU	Analyzed Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)
5	3.73E+05	27.80	7.80	1.51E+03	20.70	0.70	7.90E+03	28.00	8.00
10	6.92E+04	23.70	3.70	1.28E+03	20.60	0.60	5.62E+03	25.80	5.80
25	2.21E+04	21.50	1.50	1.70E+03	20.70	0.70	2.34E+03	23.20	3.20
35	2.03E+04	21.90	1.90	1.74E+03	21.00	1.00	2.31E+03	22.40	2.40
95	1.16E+04	21.20	1.20	1.29E+03	21.80	1.80	1.04E+03	21.90	1.90
185	4.47E+03	21.30	1.30	5.85E+02	20.90	0.90	1.14E+03	22.00	2.00
455	1.18E+03	21.50	1.50	4.43E+02	21.10	1.10	1.20E+03	22.20	2.20
845	1.50E+03	21.10	1.10	2.97E+02	21.60	1.60	7.18E+02	22.10	2.10
1805	1.64E+03	23.00	3.00	7.02E+02	24.20	4.20	7.01E+02	21.90	1.90
3600	9.31E+02	25.50	5.50	5.45E+02	26.60	6.60	2.97E+02	22.00	2.00

3.2 in./h		
Deposition	Dry	
Test ID	59-AR3.2	
Material Type	Concrete	
Spore Type	*Bg*	
Nozzle Part Number	HH-1	
Droplet Volume Mean Diameter	0.83	mm
Kinetic Energy	766.65	$J/(m^{2} \cdot h)$
Number of Nozzles Used during Test	1	
Sample Collection Time	5	s
Intensity (20 min bin measurement)	3.2	in/h
Intensity (heat map)	3.26	in/h
Intensity (Parsivel2)	4.09	in/h
Positive Control	3.15E+07	CFU
Positive Control Stdev	5.11E+06	CFU

	Coupon 1			Coupon 2			Coupon 3		
Time Stamp (s)	Average Liquid CFU	Analyzed Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)
5	4.84E+03	21.40	1.40	5.18E+03	22.90	2.90	1.78E+04	29.70	9.70
10	3.03E+03	21.20	1.20	2.89E+03	23.10	3.10	5.99E+03	26.50	6.50
25	1.89E+03	22.80	2.80	3.21E+03	23.60	3.60	5.77E+03	26.00	6.00
35	1.92E+03	24.00	4.00	3.47E+03	23.60	3.60	6.44E+03	26.40	6.40
95	1.41E+03	25.10	5.10	1.98E+03	23.00	3.00	1.68E+03	23.70	3.70
185	1.74E+03	24.80	4.80	2.32E+03	25.80	5.80	4.40E+03	29.50	9.50
455	1.44E+03	26.60	6.60	2.73E+03	25.80	5.80	9.72E+02	24.30	4.30
845	1.10E+03	29.00	9.00	2.30E+03	29.50	9.50	2.44E+03	31.70	1.70
1805	6.96E+02	29.00	9.00	1.52E+03	31.70	11.70	6.10E+02	25.40	5.40
3600	3.69E+02	29.90	9.90	3.60E+02	30.00	10.00	1.64E+02	24.60	4.60

4.0 in./h		
Deposition	Dry	
Test ID	59-AR4.0	
Material Type	Concrete	
Spore Type	*Bg*	
Nozzle Part Number	HH-50WSQ	
Droplet Volume Mean Diameter	0.85	mm
Kinetic Energy	2156	J/(m^2·h)
Number of Nozzles Used during Test	1	
Sample Collection Time	5	s
Intensity (20 min bin measurement)	3.60	in/h
Intensity (heat map)	3.66	in/h
Intensity (Parsivel2)	3.13	in/h
Positive Control	2.51E+07	CFU
Positive Control Stdev	2.60E+06	CFU

	Coupon 1			Coupon 2			Coupon 3		
Time Stamp (s)	Average Liquid CFU	Analyzed Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)
5	1.55E+04	20.68	0.68	3.25E+03	21.14	1.14	1.65E+04	21.21	1.21
10	4.57E+03	20.66	0.66	6.61E+03	21.85	1.85	1.32E+04	21.32	1.32
25	2.24E+03	20.62	0.62	2.13E+03	21.59	1.59	4.18E+03	21.16	1.16
35	3.21E+03	21.06	1.06	1.79E+03	21.39	1.39	1.48E+04	22.43	2.43
95	5.38E+03	23.40	3.40	1.45E+03	22.95	2.95	2.40E+04	25.07	5.07
185	3.38E+03	25.24	5.24	6.80E+02	24.96	4.96	3.32E+03	31.22	11.22
455	2.16E+03	28.19	8.19	3.89E+02	25.71	5.71	1.49E+03	29.79	9.79
845	1.38E+03	30.42	10.42	1.52E+02	25.95	5.95	6.61E+02	26.99	6.99
1805	1.50E+03	33.11	13.11	4.73E+01	25.93	5.93	2.34E+02	31.78	11.78
3600	3.31E+02	38.34	18.34	2.59E+01	28.55	8.55	7.35E+01	26.72	6.72

0.6 in./h		
Deposition	Dry	
Test ID	59-AR0.6	
Material Type	Concrete	
Spore Type	*Btk*	
Nozzle Part Number	HH-14WSQ	
Droplet Volume Mean Diameter	0.62	mm
Kinetic Energy	76.53	J/(m^2·h)
Number of Nozzles Used during Test	1	
Sample Collection Time	5	s
Intensity (20 min bin measurement)	0.64	in/h
Intensity (heat map)	0.57	in/h
Intensity (Parsivel2)	0.39	in/h
Positive Control	2.84E+07	CFU
Positive Control Stdev	1.28E+07	CFU

Time Stamp (s)	Coupon 1			Coupon 2			Coupon 3		
	Average Liquid CFU	Analyzed Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)
5	9.44E+04	24.70	4.70	1.62E+03	21.30	1.30	1.93E+04	26.20	6.20
10	1.96E+04	21.50	1.50	6.76E+02	20.80	0.80	8.59E+03	23.60	3.60
25	2.16E+04	22.20	2.20	8.88E+02	21.40	1.40	3.66E+03	21.80	1.80
35	1.72E+04	21.80	1.80	5.69E+02	20.70	0.70	2.31E+03	21.40	1.40
95	1.44E+04	21.80	1.80	7.95E+02	21.20	1.20	1.36E+03	21.30	1.30
185	1.46E+04	21.80	1.80	7.21E+02	21.20	1.20	4.62E+03	22.00	2.00
455	6.46E+02	20.20	0.20	7.23E+02	21.90	1.90	1.36E+03	21.30	1.30
845	1.53E+03	21.90	1.90	6.73E+02	21.70	1.70	1.38E+03	20.80	0.80
1805	7.92E+02	22.00	2.00	4.22E+02	21.10	1.10	1.01E+03	22.00	2.00
3600	2.76E+02	21.20	1.20	4.79E+02	22.80	2.80	1.96E+02	21.20	1.20

1 in./h		
Deposition	Dry	
Test ID	59-AR1	
Material Type	Concrete	
Spore Type	*Btk*	
Nozzle Part Number	GG-2.8W	
Droplet Volume Mean Diameter	0.61	mm
Kinetic Energy	43.60	J/(m^2·h)
Number of Nozzles Used during Test	1	
Sample Collection Time	5	s
Intensity (20 min bin measurement)	0.98	in/h
Intensity (heat map)	0.88	in/h
Intensity (Parsivel2)	0.48	in/h
Positive Control	3.67E+07	CFU
Positive Control Stdev	1.28E+07	CFU

	Coupon 1			Coupon 2			Coupon 3		
Time Stamp (s)	Average Liquid CFU	Analyzed Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)
5	9.50E+03	22.20	2.20	3.42E+00	22.20	2.20	5.79E+03	26.30	6.30
10	5.98E+03	21.20	1.20	1.89E+00	22.70	2.70	2.43E+03	23.80	3.80
25	5.76E+03	24.40	4.40	1.93E+00	22.00	2.00	1.92E+03	22.90	2.90
35	5.92E+03	23.50	3.50	3.98E+00	21.50	1.50	1.96E+03	22.50	2.50
95	2.39E+03	22.50	2.50	4.04E+00	21.00	1.00	1.56E+03	23.00	3.00
185	3.05E+03	22.10	2.10	1.74E+04	23.70	3.70	1.22E+03	23.10	3.10
455	1.11E+03	22.20	2.20	2.35E+04	22.80	2.80	8.25E+02	22.30	2.30
845	1.23E+03	22.90	2.90	1.08E+03	22.20	2.20	5.13E+02	22.30	2.30
1805	7.42E+02	23.20	3.20	1.08E+03	23.50	3.50	2.88E+04	23.80	3.80
3600	5.76E+02	24.00	4.00	1.20E+02	21.80	1.80	8.16E+02	24.00	4.00

3.2 in./h		
Deposition	Dry	
Test ID	59-AR3.2	
Material Type	Concrete	
Spore Type	*Btk*	
Nozzle Part Number	HH-1	
Droplet Volume Mean Diameter	0.82	mm
Kinetic Energy	797.03	$J/(m^2 \cdot h)$
Number of Nozzles Used during Test	1	
Sample Collection Time	5	s
Intensity (20 min bin measurement)	3.60	in/h
Intensity (heat map)	3.26	in/h
Intensity (Parsivel2)	4.09	in/h
Positive Control	3.15E+07	CFU
Positive Control Stdev	5.11E+06	CFU

	Coupon 1			Coupon 2			Coupon 3		
Time Stamp (s)	Average Liquid CFU	Analyzed Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)
5	2.63E+04	27.60	7.60	1.88E+05	27.30	7.30	2.09E+04	22.20	2.20
10	2.00E+04	28.80	8.80	4.22E+04	23.30	3.30	2.18E+04	25.30	5.30
25	1.37E+04	31.40	11.40	1.39E+05	25.10	5.10	1.62E+05	30.50	10.50
35	1.16E+04	30.90	10.90	1.35E+05	26.10	6.10	1.12E+05	30.20	10.20
95	7.90E+03	30.20	10.20	1.18E+04	27.60	7.60	2.94E+03	24.00	4.00
185	6.97E+03	30.70	10.70	8.31E+03	27.10	7.10	4.37E+03	24.10	4.10
455	3.15E+03	28.90	8.90	8.22E+03	26.70	6.70	2.73E+03	23.70	3.70
845	1.49E+03	26.60	6.60	3.23E+03	30.30	10.30	1.73E+03	23.80	3.80
1805	1.53E+03	29.40	9.40	2.79E+03	29.40	9.40	3.70E+02	28.00	8.00
3600	3.70E+02	29.80	9.80	1.71E+02	29.00	9.00	2.39E+02	28.80	8.80

4.0 in./h		
Deposition	Dry	
Test ID	59-AR4.0	
Material Type	Concrete	
Spore Type	*Btk*	
Nozzle Part Number	HH-50WSQ	
Droplet Volume Mean Diameter	0.82	mm
Kinetic Energy	797.03	$J/(m^{2}\cdot h)$
Number of Nozzles Used during Test	1	
Sample Collection Time	5	s
Intensity (20 min bin measurement)	0.98	in/h
Intensity (heat map)	-	in/h
Intensity (Parsivel2)	0.48	in/h
Positive Control	3.35E+07	CFU
Positive Control Stdev	2.90E+06	CFU

	Coupon 1			Coupon 2			Coupon 3		
Time Stamp (s)	Average Liquid CFU	Analyzed Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)
5	1.48E+03	20.80	0.80	1.63E+03	20.80	0.80	1.53E+03	21.10	1.10
10	3.35E+02	20.30	0.30	1.56E+03	21.50	1.50	1.92E+03	21.60	1.60
25	6.45E+02	20.80	0.80	1.85E+03	21.80	1.80	2.46E+03	21.90	1.90
35	8.90E+02	20.70	0.70	7.88E+02	21.00	1.00	1.40E+03	22.30	2.30
95	8.44E+02	21.10	1.10	1.91E+03	29.40	9.40	4.73E+03	25.40	5.40
185	4.39E+02	21.30	1.30	5.01E+03	42.20	22.20	1.14E+03	32.00	12.00
455	6.76E+02	31.40	11.40	1.37E+03	35.10	15.10	1.05E+03	37.00	17.00
845	1.39E+03	34.50	14.50	9.64E+02	37.80	17.80	1.03E+03	38.20	18.20
1805	2.65E+02	30.70	10.70	3.46E+02	40.40	20.40	2.76E+02	38.00	18.00
3600	1.26E+02	34.80	14.80	2.25E+02	41.40	21.40	1.84E+02	39.30	19.30

1.0 in./h		
Deposition	Dry	
Test ID	59-AR1-A	
Material Type	Asphalt	
Spore Type	*Bg*	
Nozzle Part Number	GG-2.8W	
Droplet Volume Mean Diameter	0.85	mm
Kinetic Energy	2156	$J/(m^{2}\cdot h)$
Number of Nozzles Used during Test	1	
Sample Collection Time	5	s
Intensity (20 min bin measurement)	3.60	in/h
Intensity (heat map)	0.92	in/h
Intensity (Parsivel2)	3.12	in/h
Positive Control	1.91E+07	CFU
Positive Control Stdev	2.83E+06	CFU

	Coupon 1			Coupon 2			Coupon 3		
Time Stamp (s)	Average Liquid CFU	Analyzed Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)
5	4.29E+03	26.50	6.50	1.73E+05	33.60	13.60	2.70E+03	29.20	9.20
10	2.55E+03	24.80	4.80	3.36E+04	24.50	4.50	1.30E+03	25.30	5.30
25	2.34E+03	24.50	4.50	1.24E+04	21.60	1.60	1.48E+03	25.30	5.30
35	1.39E+03	23.30	3.30	1.06E+03	20.70	0.70	8.53E+02	23.70	3.70
95	2.04E+03	24.00	4.00	2.64E+03	24.24	4.24	3.99E+02	22.80	2.80
185	2.32E+03	22.70	2.70	1.75E+03	23.00	3.00	5.92E+02	23.20	3.20
455	1.76E+03	27.30	7.30	4.52E+01	20.80	0.80	9.10E+02	23.80	3.80
845	5.34E+02	28.10	8.10	1.36E+02	23.60	3.60	4.21E+02	23.20	3.20
1805	5.33E+02	27.00	7.00	1.10E+02	23.90	3.90	4.04E+02	24.10	4.10
3600	7.81E+01	24.80	4.80	3.66E+01	22.50	2.50	7.72E+01	25.30	5.30

1.0 in./h		
Deposition	Dry	
Test ID	59-AR1-A	
Material Type	Asphalt	
Spore Type	*Btk*	
Nozzle Part Number	GG-2.8W	
Droplet Volume Mean Diameter	0.60	mm
Kinetic Energy	39	$J/(m^2 \cdot h)$
Number of Nozzles Used during Test	1	
Sample Collection Time	5	s
Intensity (20 min bin measurement)	1.10	in/h
Intensity (heat map)	0.92	in/h
Intensity (Parsivel2)	0.52	in/h
Positive Control	1.26E+06	CFU
Positive Control Stdev	2.86E+05	CFU

	Coupon 1			Coupon 2			Coupon 3		
Time Stamp (s)	Average Liquid CFU	Analyzed Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)
5	6.72E+03	32.60	12.60	2.51E+03	23.10	3.10	3.72E+03	26.80	6.80
10	2.28E+03	23.50	3.50	3.75E+03	21.40	1.40	5.61E+03	30.20	10.20
25	5.31E+03	34.90	14.90	4.60E+03	27.70	7.70	2.53E+03	25.20	5.20
35	3.30E+03	29.10	9.10	5.35E+03	23.90	3.90	6.70E+03	223.30	203.30
95	4.52E+02	23.50	3.50	4.03E+02	22.10	2.10	7.35E+01	20.70	0.70
185	4.20E+02	23.50	3.50	3.30E+02	22.00	2.00	3.02E+02	21.20	1.20
455	2.89E+02	23.10	3.10	2.73E+02	24.50	4.50	6.17E+01	20.90	0.90
845	8.89E+01	24.10	4.10	7.98E-01	20.10	0.10	1.04E+02	22.30	2.30
1805	1.30E+02	23.90	3.90	1.23E+02	23.80	3.80	5.18E+01	21.60	1.60
3600	4.74E+01	25.60	5.60	2.62E+01	22.80	2.80	3.75E+01	23.80	3.80

4.0 in./h		
Deposition	Dry	
Test ID	59-AR4.0	
Material Type	Asphalt	
Spore Type	*Btk*	
Nozzle Part Number	HH-50WSQ	
Droplet Volume Mean Diameter	0.82	mm
Kinetic Energy	894	$J/(m^{2} \cdot h)$
Number of Nozzles Used during Test	1	
Sample Collection Time	5	s
Intensity (20 min bin measurement)	2.45	in/h
Intensity (heat map)	2.40	in/h
Intensity (Parsivel2)	1.98	in/h
Positive Control	1.26E+07	CFU
Positive Control Stdev	2.06E+06	CFU

	Coupon 1			Coupon 2		
Time Stamp (s)	Average Liquid CFU	Analyzed Volume (mL)	Collected Volume (mL)	Average Liquid CFU	Sample Volume (mL)	Collected Volume (mL)
5	8.33E+04	31.90	11.90	5.05E+04	29.90	9.90
10	9.67E+04	31.70	11.70	2.80E+04	28.10	8.10
25	5.31E+04	24.80	4.80	6.08E+04	24.80	4.80
35	3.40E+04	28.10	8.10	8.91E+03	22.00	2.00
95	2.47E+02	21.70	1.70	1.21E+04	26.90	6.90
185	4.81E+03	24.50	4.50	5.06E+04	24.00	4.00
455	7.75E+02	24.60	4.60	5.73E+03	25.30	5.30
845	2.16E+03	26.50	6.50	1.04E+03	26.10	6.10
1805	5.61E+02	26.70	6.70	9.84E+02	28.10	8.10
3600	8.00E+02	32.00	12.00	4.53E+02	30.20	10.20

Appendix F. Spore Washoff Procedure-Channel

For these experiments, spores were dry-inoculated onto the surface of a concrete coupon and positioned at a 5% slope in the custom channelized flow apparatus. Runoff samples that correlate with various time points of interest and positive control coupons (concrete coupons that have been dry-inoculated and sampled with wipes) were collected.

Preparation

Sterilize the following materials in the airlock (4 hours, 200 ppm vaporous hydrogen peroxide):

- Overflow tank
- Aerosol dose apparatuses (4)

Sterilize the following materials in the autoclave (250°C gravity cycle):

- Stainless steel coupons (4)
- 500 mL Nalgene bottles with caps (20)
- 14x14" concrete coupons (4)

Sterilize the deionized water tank as follows:

- Pour one gallon of germicidal bleach into the tank and fill the tank with DI water.
- Empty the tank into the sump.
- Fill and empty the tank two times with DI water.
- Fill the tank with deionized water.

Day 1

- Set up tables with bench liner. Remove a metered dose inhaler (E7) from the refrigerator.
- Assemble three stainless steel coupons with aerosol dose apparatuses.
- Assemble one concrete coupon with apparatus.
- Perform sterility swabs on the concrete coupon, one stainless steel coupon and one aerosol dose apparatus.
- Inoculate the test set of coupons.

Day 2

- Transfer the channel outside, level, and cover the weir and area before the coupon holder with sterilized aluminum foil.
- Establish a flow rate without the coupon. Record a few measurements to ensure that this setting achieves the desired flow rate.
- Take a 50-mL blank sample from the established flow in a specimen cup to test sterility.
- Stop the flow and dry the test tank with a clean cloth.
- Set the concrete coupon in the channel and seal the surrounding area with door caulk.
- Start the flow at the desired flowrate
- Fill the tank to the top of the weir with water and ensure it does not overflow.
- Start a timer when the first drop of sample flows down the basin. Simultaneously begin sample collection as follows:
    - For the first 45 seconds, a four-person team will be positioned at the collection end of the overflow tank. Two samplers collect liquid samples into Nalgene

bottles by opening their respective outlet valves, then closing the valves after a collection time of 5 seconds (per sample). The third and fourth person will assist the samplers by receiving and capping collected samples, and supplying empty Nalgene bottles to the samplers.

  - Collect one sample between 0 and 5 seconds (sampler 1)
  - Collect one sample between 5 and 10 seconds (sampler 2)
  - Collect one sample between 17 and 22 seconds (sampler 1)
  - Collect one sample between 40 and 45 seconds (sampler 2)
  - Discard the runoff between 45 seconds and 88 seconds
  - Collect one sample at 88 seconds
  - Discard the runoff between 93 seconds and 188 seconds
  - Collect one sample at 188 seconds
  - Discard the runoff
  - Collect one sample at 397 seconds
  - Discard the runoff
  - Collect one sample at 829 seconds
  - Discard the runoff
  - Collect one sample at 1727 seconds
  - Discard the runoff
  - Collect one sample at 3592 seconds

- Stop the deionized water pump and discard the remaining runoff.
- Record the volumes of each liquid sample.
- Wipe sample the three inoculation control coupons.
- Deliver all samples to the onsite microbiology laboratory with a chain of custody form.

Appendix G. Spore Washoff Data - Channel

25 mL/s

Deposition	Dry	
Test ID	59-A025-D1	
Sample Collection Time	5	s
Flow Rate	25	mL/s
Positive Control	2.52E+07	CFU
Time Stamp (s)	Average Liquid CFU	Sample Volume
5	1.59E+05	16.04
10	7.62E+04	21.46
22	5.35E+04	22.84
45	3.56E+05	29.58
93	4.27E+04	26.30
193	6.04E+04	25.62
402	5.03E+03	25.60
834	1.95E+03	25.96
1732	3.81E+02	27.20
3597	7.51E+02	25.04

50 mL/s

Deposition	Dry		Deposition	Dry	
Test ID	59-A050-D2		Test ID	59-AO50-D3	
Sample Collection Time	5	s	Sample Collection Time	5	s
Flow Rate	50	mL/s	Flow Rate	50	mL/s
Positive Control	4.68E+07	CFU	Positive Control	3.84E+07	CFU
Positive Control Stdev	4.41E+06	CFU	Positive Control Stdev	1.16E+07	CFU
Time Stamp (s)	Average Liquid CFU	Sample Volume (mL)	Time Stamp (s)	Average Liquid CFU	Sample Volume (mL)
5	1.50E+06	39.02	5	1.76E+06	14.78
10	1.27E+06	43.88	10	8.49E+05	33.26
22	2.96E+05	46.04	22	2.53E+05	47.56
45	8.93E+04	49.06	45	5.50E+04	51.54
93	1.98E+04	48.06	93	7.98E+04	48.26
193	1.40E+04	52.16	193	1.00E+04	51.28
402	1.38E+04	47.10	402	6.94E+03	52.90
834	3.62E+03	49.58	834	1.29E+03	54.90
1732	5.57E+02	49.06	1732	3.54E+02	52.66
3597	1.73E+02	49.12	3597	1.15E+02	55.64

75 mL/s					
Deposition	Dry		Deposition	Dry	
Test Date	59-A075-D1		Test ID	59-A075-D2	
Sample Collection Time	5	s	Sample Collection Time	5	s
Flow Rate	75	mL/s	Flow Rate	75	mL/s
Positive Control	2.65E+07	CFU	Inoculation Control	4.20E+07	CFU
Positive Control Stdev	3.99E+06	CFU	Positive Control Stdev	1.06E+07	CFU
Time Stamp (s)	Average Liquid CFU	Sample Volume (mL)	Time Stamp (s)	Average Liquid CFU	Sample Volume (mL)
5	5.67E+06	62.98	5	3.75E+06	45.72
10	8.22E+05	63.22	10	2.65E+06	58.40
22	3.91E+05	68.58	22	7.16E+05	69.86
45	1.35E+05	67.72	45	1.37E+05	62.66
93	2.10E+04	70.88	93	3.98E+04	75.72
193	8.50E+03	70.82	193	2.51E+04	72.74
402	4.07E+03	73.58	402	2.78E+03	85.78
834	8.21E+02	68.42	834	3.95E+03	75.30
1732	1.90E+02	68.92	1732	1.36E+03	67.82
3597	2.83E+02	73.16	3597	6.65E+02	81.86

100 mL/s					
Deposition	Dry		Deposition	Dry	
Test ID	59-AO100-D1		Test ID	59-AO100-D2	
Sample Collection Time	5	s	Sample Collection Time	5	s
Flow Rate	100	mL/s	Flow Rate	100	mL/s
Positive Control	3.55E+07	CFU	Positive Control	2.52E+07	CFU
Positive Control Stdev		CFU	Positive Control Stdev		CFU
Time Stamp (s)	Average Liquid CFU	Sample Volume (mL)	Time Stamp (s)	Average Liquid CFU	Sample Volume (mL)
5	1.69E+05	26.96	5	3.05E+06	50.02
10	6.79E+05	62.58	10	4.54E+05	63.46
22	2.96E+05	64.90	22	4.64E+05	68.22
45	9.54E+04	78.56	45	8.31E+04	80.92
93	1.55E+04	83.92	93	2.71E+04	99.50
193	2.86E+04	96.94	193	5.18E+03	97.34
402	3.88E+03	89.48	402	1.63E+03	96.76
834	1.59E+03	105.30	834	1.35E+03	94.14
1732	1.10E+04	95.54	1732	2.02E+03	101.12
3597	7.59E+02	94.88	3597	1.10E+03	86.88

150 mL/s					
Deposition	Dry		Deposition	Dry	
Test ID	59-AO150-D1		Test ID	59-AO150-D2	
Sample Collection Time	5	s	Sample Collection Time	5	s
Flow Rate	150	mL/s	Flow Rate	150	mL/s
Positive Control	4.96E+07	CFU	Positive Control	3.55E+07	CFU
Positive Control Stdev	1.39E+07	CFU	Positive Control Stdev	9.64E+06	CFU
Time Stamp (s)	Average Liquid CFU	Sample Volume (mL)	Time Stamp (s)	Average Liquid CFU	Sample Volume (mL)
5	5.90E+06	81.92	5	4.35E+05	35.26
10	1.77E+06	96.82	10	1.04E+06	65.98
22	1.61E+05	91.94	22	6.99E+05	101.34
45	1.16E+05	116.18	45	5.19E+05	120.70
93	1.38E+05	138.08	93	1.13E+05	144.36
193	3.18E+04	157.24	193	2.31E+04	154.16
402	9.72E+03	138.90	402	5.46E+03	148.82
834	7.65E+03	152.94	834	7.57E+02	141.96
1732	1.32E+03	140.60	1732	5.37E+02	148.16
3597	4.32E+02	143.94	3597	6.57E+02	145.94

Appendix H. Channel Velocity Measurements

Coupon Water Height at 50 mL/s (in)					
	Column				
Row	A	B	C	D	E
1	0.061	0.083	0.09	0.098	0.07
2	0.065	0.046	0.058	0.061	0.032
3	0.047	0.068	0.083	0.075	0.034
4	0.05	0.056	0.055	0.028	0.001
5	0.066	0.085	0.077	0.068	0.006

Coupon Water Height at 75 mL/s (in)					
	Column				
Row	A	B	C	D	E
1	0.047	0.056	0.074	0.047	0.047
2	0.048	0.049	0.074	0.058	0.042
3	0.069	0.066	0.072	0.045	0.01
4	0.053	0.075	0.06	0.043	0.014
5	0.056	0.073	0.078	0.07	0.032

Coupon Water Height at 100 mL/s (in)					
	Column				
Row	A	B	C	D	E
1	0.066	0.069	0.093	0.068	0.072
2	0.069	0.045	0.084	0.067	0.048
3	0.048	0.082	0.068	0.055	0.033
4	0.054	0.075	0.081	0.049	0.031
5	0.05	0.066	0.085	0.07	0.048

Coupon Water Height at 150 mL/s (in)					
	Column				
Row	A	B	C	D	E
1	0.043	0.06	0.093	0.113	0.089
2	0.079	0.047	0.086	0.102	0.062
3	0.039	0.045	0.072	0.07	0.035
4	0.046	0.057	0.074	0.046	0.005
5	0.102	0.098	0.092	0.095	0.051

Volumetric Velocity Equation

$$U_v = \frac{Q}{A_c} = \frac{Q[\frac{mL}{s}]}{h[in] * b[in]} = \frac{Q\left[\frac{mL}{s}\right] \; * 1e-6[\frac{m^3}{mL}]}{\left(\frac{7.84}{2}\;[in]\right) * h[in] * 0.000645[\frac{m^2}{in^2}]}$$

Manning's Velocity Equation

$$U_m = \frac{R^{2/3} * \sqrt{S}}{n} = \frac{(\frac{A_c}{P})^{2/3}\left[m^{\frac{2}{3}}\right] * \sqrt{S}[\frac{m}{m}]}{n[\frac{s}{\sqrt[3]{m}}]} = \frac{(\frac{h*b}{2*h+b})^2[\frac{m^2}{m}] * \sqrt{S}[\frac{m}{m}]}{n[\frac{s}{\sqrt[3]{m}}]}$$

Where:

$$A_t = l * w \qquad P = 2 * h + b$$

$$R = \frac{A_c}{P} \qquad b = \frac{A_p}{2}$$

$$A_c = h * b \qquad h = dh - href$$

$$A_p = \frac{A_t}{25}$$

Legend	
Q	Volumetric Flowrate
A_t	Total Surface Area
A_p	Partitioned Area
A_c	Cross Sectional Area
U_v	Volumetric Velocity
U_m	Manning Velocity
R	Hydraulic Radius
S	Slope
n	Manning Coefficient
P	Perimeter
l	Length
w	Width
h	water height
dh	Water + Concrete height
href	Reference to concrete height
b	area width

Appendix I. Spore Washoff Procedure-Spray

Purpose

Coupons were inoculated with bacillus spores (*Bg* or *Btk*) and decontaminated using a garden hose with a nozzle on the shower setting or a pressure washer with the 15-degree spray angle tip. The coupons will have an inoculated area of approximately 4.25 in. x 4.25 in. and will be sprayed at approximately 34 in. away from the surface of the coupon. The inoculated area corresponds to the theoretical coverage achieved by the pressure washer at the specified spray height.

Day 1

- Prior to coupon inoculation, swab samples of a representative coupon and inoculation control coupon will be collected.
- Coupons will be inoculated (loaded) with spores from a metered dose inhaler using the procedure detailed in Miscellaneous Operating procedure (MOP) 3161M that uses an aerosol dosing apparatus. The inoculation procedure will involve raising the apparatus to the same level as the coupon, clamping the coupon onto a 14" x 14" stainless steel piece with a 5.5-in. x 5.5-in. cutout, and inoculating the coupon so that an even distribution of spores meets the coupon to ensure that a 14-in. x 14-in. area gets completely inoculated. If needed, cover any gaps between the 14-in. x 14-in. stainless steel and the 5.5-in. x 5.5-in. coupon to prevent cross contamination and escaping spores.
- Once the aerosol dosing apparatus has been secured to the coupon, place the metered dose inhaler on the top, open the slide, and activate the inhaler.
- Following inoculation, close the slide and remove the inhaler.
- Repeat for each coupon.
- Record the initial and final inhaler mass (verify scale calibration) in the inoculation log.
- Allow at least 18 hours after inoculating the coupons before testing.

Day 2

Pre-Test Activities:

- Calibrate a pH meter using pH buffer solutions: 4.0, 7.0, and 10.0
- Determine the free available chlorine of the bleach feed stock. If the hypochlorite concentration is less than 7%, **DO NOT USE.**
- Prepare 4 L of pH adjusted bleach with a free available chlorine of approximately 7,900 mg/L. The pH adjusted bleach will be prepared using a volumetric ratio of 1:1:8 Clorox® Concentrated Germicidal bleach: 5% acetic acid: deionized water
    - Measure the free available chlorine using a HACH® kit. Record measurement in laboratory notebook.
    - Measure the pH and temperature of the pH adjusted bleach with calibrated pH meter. Record measurements in laboratory notebook.
    - Record the time the pH adjusted bleach was prepared
- Transfer pH adjusted bleach into a sterile SHURflo backpack sprayer.

- Spray the wash-down chamber with pH adjusted bleach and allow a 15-minute contact time with collection port closed.
- Rinse the chamber with deionized water.
- As water drains from the chamber, collect a 100-mL sample.
- Determine the free available chlorine of the sample. If sample is clear (or approximately the same free available chlorine of tap water), then the sample is free of chlorine; if not, then re-rinse the chamber until no free available chlorine is present.

Coupon Wash-down and Sampling:

1. Set up a table with bench liner for sample handling.
2. Connect the hose to the pressure washer and power on the pressure washer or garden spray nozzle. If using the pressure washer, allow time to pressurize the water (when powered on, the washer makes plenty of noise; once it quiets down, the water is pressurized).
3. Collect ~100 mL of water from the pressure washer outlet. *NOTE: Remove the spray tip before doing this.
4. Place the desired spray tip on the pressure washer and spray water so that any air that may be stuck is removed when the line is purged to ensure that the coupon is sprayed with the correct angle and force.
5. Aseptically place the procedural blank coupon on the load cell. Ensure all ports except the spraying port are covered.
6. Open and place a sterile Nalgene bottle directly underneath the collection port.
7. Start the Portable Data Acquisition (PDAQ) (force sensor) to record load cell measurements.
8. Go up to the exact height of the wash-down chamber port opening and spray the coupon straight down vertically for 5 seconds.
9. Collect, cap, and adequately label the Nalgene bottle in preparation to deliver sample to the onsite microbiology laboratory.
10. Aseptically remove the procedural blank coupon. Ensure all ports except the spraying port are covered.
11. Rinse the wash-down basin with copious amounts of water.
12. Open and place a second sterile Nalgene bottle directly underneath the collection port.
13. Collect a rinse sample of the basin to check for any potential residual spores.
14. Collect, cap, and adequately label the Nalgene bottle in preparation for delivery of sample to the biolab.
15. Remove the aerosol dose apparatus from a test coupon and aseptically place on the load cell. Ensure all ports except the spraying port are covered.
16. Open and place a sterile Nalgene bottle directly underneath the collection port.
17. Start the PDAQ. Properly name the file and write the file name down in the notebook.
18. Go up to the exact height of the wash-down chamber port opening and spray the coupon straight down vertically for 5 seconds.

19. Record the coupon identification (ID), duration of spray, and time in the notebook.
20. Collect and cap the Nalgene bottle, adequately label in preparation to deliver sample to the biolab.
21. Aseptically remove the test coupon from the load cell. Ensure all ports except the spraying port are covered.
22. Rinse the wash-down basin with copious amounts of water.
23. Open and place a second sterile Nalgene bottle directly underneath the collection port.
24. Collect a rinse sample of the basin to check for any potential residual spores.
25. Collect, cap, and adequately label the Nalgene bottle in preparation to deliver sample to the biolab.
26. Repeat steps 15 through 25 for n number of test coupons.
27. Perform wipe samples of the coupons listed below following the listed instructions.

The coupons will be removed, and wipe sampled with polyester rayon blend wipes using MOP 3199 as a guide. The sample will be placed in a conical tube containing 10 mL of phosphate buffered saline with 0.05% TWEEN®20 (PBST).

Appendix J. Spore Washoff Data - Spray

Average of Replicate Coupons			
Test IDs	1BCH, 1BCHb		
Material Type	Concrete		
Spore Type	*Bg*		
Spray Method	Garden Hose		
Spray Orientation	Vertical		
Spray Distance	34	in.	
Spray Time	5	s	
Number of Replicates	5	per test	
Average Positive Control Log CFU	7.18		
Stdev Positive Control Log CFU	6.56		
Total Average Applied Energy	0.44	J	
Applied Energy Standard Error	1.48E-03	J	
Energy Flux	16110	J/m^2-h	
Coupon	Average Log CFU	Standard Error	Avg % Removal
TC1	6.11		93%
TC2	6.08		94%
TC3	6.09		94%
TC4	6.11		93%
TC5	6.03		94%
Average	6.08	0.011	94%

Average of Replicate Coupons			
Test IDs	1BBH		
Material Type	Brick		
Spore Type	*Bg*		
Spray Method	Garden Hose		
Spray Orientation	Vertical		
Spray Distance	34	in.	
Spray Time	5	s	
Number of Replicates	5	per test	
Average Positive Control Log CFU	7.21		
Stdev Positive Control Log CFU	6.20		
Total Average Applied Energy	0.20	J	
Applied Energy Standard Error	1.48E-03	J	
Energy Flux	7233	J/m^2-h	
Coupon	Average Log CFU	Standard Error	Avg % Removal
TC1	6.06		93%
TC2	6.14		91%
TC3	6.17		90%
TC4	6.08		92%
TC5	6.14		91%
Average	6.12	0.02	91%

Average of Replicate Coupons			
Test IDs	1BAH		
Material Type	Asphalt		
Spore Type	*Bg*		
Spray Method	Garden Hose		
Spray Orientation	Vertical		
Spray Distance	34	in.	
Spray Time	5	s	
Number of Replicates	5	per test	
Average Positive Control Log CFU	7.08		
Stdev Positive Control Log CFU	6.77		
Total Average Applied Energy	0.09	J	
Applied Energy Standard Error	1.48E-03	J	
Energy Flux	3353	J/m^2-h	
Coupon	Average Log CFU	Standard Error	Avg % Removal
TC1	5.90		93%
TC2	5.67		96%
TC3	5.91		93%
TC4	5.70		95%
TC5	5.79		94%
Average	5.79	0.049	94%

Average of Replicate Coupons			
Test IDs	1BGH		
Material Type	Glass		
Spore Type	*Bg*		
Spray Method	Garden Hose		
Spray Orientation	Vertical		
Spray Distance	34	in.	
Spray Time	5	s	
Number of Replicates	5	per test	
Average Positive Control Log CFU	7.15		
Stdev Positive Control Log CFU	6.54		
Total Average Applied Energy	0.14	J	
Applied Energy Standard Error	1.48E-03	J	
Energy Flux	5034	J/m^2-h	
Coupon	Average Log CFU	Standard Error	Avg % Removal
TC1	5.14		99%
TC2	4.81		99%
TC3	5.05		99%
TC4	5.18		99%
TC5	5.13		99%
Average	5.06	0.067	99%

Average of Replicate Coupons			
Test IDs	3BCH		
Material Type	Concrete		
Spore Type	*Bg*		
Spray Method	Pressure Washer		
Spray Orientation	Vertical		
Spray Distance	34	in.	
Spray Time	5	s	
Number of Replicates	5	per test	
Average Positive Control Log CFU	7.44		
Stdev Positive Control Log CFU	6.92		
Total Average Applied Energy	0.57	J	
Applied Energy Standard Error	1.48E-03	J	
Energy Flux	21146	J/m^2-h	
Coupon	Average Log CFU	Standard Error	Avg % Removal
TC1	6.14		93%
TC2	6.45		85%
TC3	5.90		96%
TC4	6.18		92%
TC5	6.32		89%
Average	6.20	0.093	91%

Average of Replicate Coupons			
Test IDs	3BBH		
Material Type	Brick		
Spore Type	*Bg*		
Spray Method	Pressure Washer		
Spray Orientation	Vertical		
Spray Distance	34	in.	
Spray Time	5	s	
Number of Replicates	5	per test	
Average Positive Control Log CFU	7.17		
Stdev Positive Control Log CFU	6.50		
Total Average Applied Energy	0.79	J	
Applied Energy Standard Error	1.48E-03	J	
Energy Flux	29218	J/m^2-h	
Coupon	Average Log CFU	Standard Error	Avg % Removal
TC1	5.88		95%
TC2	6.02		93%
TC3	5.98		94%
TC4	6.00		93%
TC5	5.75		96%
Average	5.93	0.050	94%

Average of Replicate Coupons			
Test IDs	3BAH		
Material Type	Asphalt		
Spore Type	*Bg*		
Spray Method	Pressure Washer		
Spray Orientation	Vertical		
Spray Distance	34	in.	
Spray Time	5	s	
Number of Replicates	5	per test	
Average Positive Control Log CFU	7.00		
Stdev Positive Control Log CFU	6.35		
Total Average Applied Energy	0.44	J	
Applied Energy Standard Error	1.48E-03	J	
Energy Flux	16385	J/m^2-h	
Coupon	Average Log CFU	Standard Error	Avg % Removal
TC1	5.55		97%
TC2	5.46		97%
TC3	5.64		96%
TC4	5.53		97%
TC5	5.70		95%
Average	5.58	0.042	97%

Average of Replicate Coupons			
Test IDs	3BGH		
Material Type	Glass		
Spore Type	*Bg*		
Spray Method	Pressure Washer		
Spray Orientation	Vertical		
Spray Distance	34	in.	
Spray Time	5	s	
Number of Replicates	5	per test	
Average Positive Control Log CFU	7.05		
Stdev Positive Control Log CFU	6.03		
Total Average Applied Energy	0.61	J	
Applied Energy Standard Error	1.48E-03	J	
Energy Flux	22632	J/m^2-h	
Coupon	Average Log CFU	Standard Error	Avg % Removal
TC1	5.60		97%
TC2	5.64		97%
TC3	5.69		96%
TC4	5.86		94%
TC5	5.41		98%
Average	5.64	0.073	96%

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